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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**DECISION CRITERIA FOR THE USE OF CANNON-FIRED
PRECISION MUNITIONS**

by

Harold L. La Rock, II

June 2005

Thesis Advisor:
Second Reader:

Alan Washburn
Jon Christensen

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 2005	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE: Decision Criteria For The Use Of Cannon-Fired Precision Munitions			5. FUNDING NUMBERS	
6. AUTHOR(S) La Rock, II, Harold L.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) The U.S. Army and Marine Corps are developing guided munitions for cannon artillery. These munitions provide a significant increase in range and accuracy, but the tactics, techniques, and procedures used to employ them have yet to be developed. This study is intended to assist with that development by providing a method to determine when to use these munitions rather than conventional munitions in order to achieve a tactical-level commander's desired objectives. A combination of multi-attribute utility theory and simulation are used to determine the best ammunition (precision or conventional) to fire under certain battlefield conditions. The simulation, developed by the U.S. Army Research Laboratory, provides results on the full range of artillery effects by varying the different battlefield conditions that have the greatest effect on the accuracy of artillery. The results of simulated artillery fire missions are studied to determine the combination of battlefield conditions that produce the best results for each type of ammunition. A decision model is used to account for a commander's expected preferences based on tactical considerations. The results vary greatly depending on the battlefield conditions and the commander's preferences. One type of projectile does not clearly dominate the other.				
14. SUBJECT TERMS Field Artillery, Precision-Guided Munitions, Munitions Effects, Cannon, Fire Support, Firing Theory, Gunnery			15. NUMBER OF PAGES 109	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

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**DECISION CRITERIA FOR THE USE OF CANNON-FIRED PRECISION
MUNITIONS**

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Major, United States Army
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

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ABSTRACT

The U.S. Army and Marine Corps are developing guided munitions for cannon artillery. These munitions provide a significant increase in range and accuracy, but the tactics, techniques, and procedures used to employ them have yet to be developed. This study is intended to assist with that development by providing a method to determine when to use these munitions rather than conventional munitions in order to achieve a tactical-level commander's desired objectives.

A combination of multi-attribute utility theory and simulation are used to determine the best ammunition (precision or conventional) to fire under certain battlefield conditions. The simulation, developed by the U.S. Army Research Laboratory, provides results on the full range of artillery effects by varying the different battlefield conditions that have the greatest effect on the accuracy of artillery. The results of simulated artillery fire missions are studied to determine the combination of battlefield conditions that produce the best results for each type of ammunition.

A decision model is used to account for a commander's expected preferences based on tactical considerations. The results vary greatly depending on the battlefield conditions and the commander's preferences. One type of projectile does not clearly dominate the other.

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ACKNOWLEDGMENTS

The author would like acknowledge the financial support of the National Security Analysis Department at Johns Hopkins University's Applied Physics Laboratory. The author is sincerely grateful to Joseph K. Wald and Carolyn Patterson of the Weapons and Materials Research Directorate at the Army Research Laboratory. The work they did modifying the Mortar Mission Model and providing the data needed was invaluable and much appreciated. The author is very appreciative of Professor Alan Washburn for his candid advice and prompt feedback. The author is also thankful to COL Saverio Manago and LTC Jon Christensen for their guidance and encouragement.

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EXECUTIVE SUMMARY

The U. S. Army and Marine Corps Field Artillery have invested in the research and development of precision-guided munitions (PGM). The technology is ready, but the tactics, techniques, and procedures used to employ them have not yet been developed and practiced. It's my intent that this research assists the field artillery community with developing that doctrine.

The problem being addressed is under what conditions a brigade-level tactical commander would decide to employ cannon-fired precision munitions rather than conventional munitions. There is no doubt that PGM are suited for precision fires, which involve firing one weapon at an accurately located point target. This study challenges that they should also be used for area fires, which involve firing many weapons in order to spread the effects over a large area.

Many budgetary-minded people would be repulsed by the thought of using precision munitions for area fire. The munitions are too expensive to fire in large amounts required for an area fire mission. Conventional munitions are usually preferred for area fire because we assume that we can shoot more of them at lower cost to achieve the same effect. However, there are conditions in which using PGM are worth the monetary cost.

The results of this study show that, on average, PGM provide better effects on the enemy and reduce the risk to friendly forces and civilian personnel. In general, PGM are worth the cost when both non-enemy (civilian and friendly) personnel are in close proximity to the target and we have an accurate observer. This is not the only case. The preferred choice of munitions employment depends on several battlefield conditions and the commander's preferences.

Precision guidance systems provide improved accuracy of our artillery. This study compares two high-explosive, point-detonating munitions with the same lethal areas in order to determine the benefits of the improved accuracy. One has a precision guidance system and the other does not. Both are fired in the same artillery fire missions

under various conditions. Half of the fire missions involve firing adjustment rounds (projectiles) to adjust the aim point of the guns. The other half do not.

This study focuses on four battlefield conditions that influence the employment decision. We have already mentioned non-enemy personnel in close proximity to the target. The other three conditions are chosen because they are the primary variables affecting accuracy (the target, target location error, and the gun-to-target range).

The targets in this study represent stationary formations of personnel on open, flat terrain. We assume that a tactical commander has three objectives when attacking these targets with field artillery. The objectives are to maximize effects on enemy personnel, minimize effects on non-enemy personnel, and minimize the cost of firing. These objectives are influenced by the employment decision as well as the four battlefield conditions.

Decision criteria were developed to measure the achievement of each of the commander's objectives. There are two decision criteria that are used to represent the objective of maximizing the effects on the enemy. Fractional damage (FD) represents the proportion of casualties produced on the target. Fractional suppression (FS) represents the proportion of enemy personnel unable to fire on friendly personnel during a given time interval. "Keep-Out" distance, K , represents the minimum distance at which a standing non-enemy person has a very low probability (0.01) of becoming a casualty. Cost is represented by the number of days required to re-supply the ammunition fired during a fire mission. It is determined from the controlled supply rate (CSR).

A stochastic simulation was used to determine the values of these four criteria. The model chosen was a modified version of the Mortar Mission Model developed by the Army Research Laboratory, Aberdeen Proving Ground. It is a Monte Carlo, discrete-event simulation model that measures the number of rounds fired, the enemy casualties, and the number of enemy personnel suppressed over a given time interval. It also produces contour maps that display the casualty effects and the value of K .

The values obtained from the simulation were analyzed to ensure they "made sense". They were also analyzed to determine which employment options produced

better values. The analysis showed that precision munitions, on average, produced more favorable values of FS, FD, and K. They also require less adjustment rounds.

Since this is a decision problem, the preferences of a military commander cannot be ignored. Utility functions were assigned to the decision criteria to measure how well they achieve their corresponding commander's objective. The functions are based on military doctrine, such as target analysis and risk management. These functions were combined into an additive utility function to measure each employment option's level of achievement of all three of the commander's objectives.

Determining weights that represent the relative importance a commander would place on one criterion over the other is difficult. A staff officer can compute the appropriate weights for the commander with the use of the analytical hierarchy process. This process requires the officer to make pair-wise comparisons of the decision criteria. Guidelines for comparing the relative importance of the decision criteria were developed to assist the staff officer. The guidelines are based on information the officer would receive from the commander's guidance and tactical situation.

A Microsoft Excel workbook was developed that allows the staff officer to input the target location error, the target, the gun-to-target range, CSR, and the pair-wise comparisons. It provides an employment solution in the form of projectile type (conventional or precision) and mission type (with or without adjustment). The staff officer determines and recommends the best choice for the commander.

Higher risk to non-enemy personnel increases the use of precision munitions and higher cost reduces the use of them. The solution depends highly on the weights. When a commander gives "Keep-Out" distance the highest weight, the solution is normally to use precision weapons regardless of cost.

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I. INTRODUCTION

A. BACKGROUND

The majority of battles in the future will reasonably be assumed to occur in urban terrain where there is greater risk of injury to civilians and collateral damage to buildings, especially schools, religious structures, and homes. Recent events have illustrated the need for very accurate artillery fire impacting within 200-500 meters of friendly forces. During the Battle of Falluja in 2004, “we routinely had 155-mm and 120-mm fires within 200 meters of friendly forces.” (Cobb et. al., 2005, p.24) Cannon fire using conventional (“dumb”) munitions proved effective enough, but new developments in precision-guided munitions (PGM) should improve the effectiveness of artillery while minimizing the risk of collateral damage and fratricide.

Artillery fire that is ineffective against the enemy and inadvertently effective on civilians or friendly forces near the enemy is the “worst-case” scenario for field artillerymen. That scenario is the reason artillerymen have struggled over centuries to make their fire as accurate as possible by improving their technology and their procedures. The most recent technological advancement in field artillery history is the use of a global positioning system (GPS)/inertial navigation system (INS) to guide cannon-fired artillery munitions.

The U.S. Army and Marine Corps Field Artillery have programs to provide cannon and rocket artillery with GPS/INS-guided precision munitions. These programs include the Excalibur 155mm Unitary Precision Munitions, the Projectile Guidance Kit (PGK), and the Guided Multiple Launch Rocket System (G-MLRS) munitions. The PGK is a course correcting fuse that converts existing conventional 105mm and 155mm ammunition into PGMs, but is not ready for fielding. The Excalibur and G-MLRS are entirely new and projected for fielding in late FY06.

Once fielded, the next step is to determine how these munitions are going to be employed. Their introduction will provide the Army and Marine Corps field artillery a significant improvement in range and accuracy. Unfortunately, the doctrine for the use of these new munitions has yet to be written and practiced.

B. OBJECTIVES

The purpose of this study is to assist a tactical-level commander of an Army Unit of Action (UA) with the decision of which type of munitions (conventional or precision-guided) to employ for a given set of battlefield conditions. We do this by exploring the cost-effectiveness of high-explosive, cannon-fired precision munitions versus conventional munitions for specific sets of battlefield conditions. We compare them in both the precision fire and area fire roles.

C. THE COMMANDER'S DECISION PROBLEM

First, we must determine a commander's objectives, and then provide decision criteria to assist the commander with the choice that best meets those objectives. Once the decision criteria are determined, we must determine what battlefield conditions affect them. Finally, we will be able to provide a commander with a recommended optimal choice of munitions when a specific set of battlefield conditions exist.

1. The Commander's Fundamental Objectives

If PGM were inexpensive and not a burden on the logistics system, we can assume that a commander would always choose to employ them. They are more accurate and presumably fewer would be required to hit the target than conventional munitions. This may be a possibility in the future, but for now we assume that precision munitions are fielded in short supply due to fiscal and logistic constraints. Therefore, we can assume that we would always choose to employ conventional munitions. We can presumably fire more of them at a lower cost and achieve the same effect as the precision munitions.

If the commander's fundamental objectives are to maximize the effectiveness of fires on the enemy while minimizing the cost of firing, then we could assume that the decision would be dominated by the choice of conventional munitions and this paper would not be written. Unfortunately, there is another situation on the battlefield that complicates this decision. It is the presence of non-enemy personnel and property in close proximity to the enemy target. Non-enemy personnel include friendly and neutral forces as well as civilians. As mentioned earlier, we assume that the risk of civilian casualties and collateral damage will be more likely in the future. Therefore, a UA commander must consider this risk when deciding which ammunition to employ.

The introduction of this complication provides a UA commander with three fundamental objectives for every fire mission.

1. Maximize the effects of fire on the enemy.
2. Minimize the effects of fire on non-enemy.
3. Minimize the cost of firing.

The primary objective of an artillery fire mission is always to maximize effects on the enemy, so we cannot just consider the other two objectives alone. If a commander only wants to maximize effects on the enemy and minimize the effects on non-enemy without considering cost, then it can be shown that precision munitions are better. The optimal choice of munitions that accomplishes all three objectives simultaneously is much more difficult to determine and is the focus of this study.

2. Battlefield Conditions Influencing the Decision

The commander has very little information before making the decision that would influence his choice between PGM and conventional munitions. Conditions on a battlefield are dynamic and each fire mission will have its own unique variables that won't be known until an observer (sensor) initiates the fire mission.

The primary variables known to the commander before making a decision are determined from information obtained from the observer. They include the observer's accuracy (target location error), the gun-to-target (GT) range, the target description (type, size, and shape), and the proximity of non-enemy personnel to the perimeter of the target. There are other factors that could influence the decision, including method of control, rate of fire, and sheaf (pattern of bursts) used. These factors are held constant in this thesis, but are recommended for further study.

We will refer to the variables, target location error (TLE), GT range, target description, and proximity of non-enemy personnel, as battlefield conditions. The question to answer is, "How do these conditions affect the commander's objectives?" This study attempts to answer this question with the use of Monte Carlo simulation. Once this question is answered, the decision depends on the commander's preferences and how he weights the importance of each objective.

The structure of the decision problem is represented by the influence diagram in Figure 1. The rectangular node represents the decision that the commander must make in choosing which type of projectile to employ (precision or conventional). The double-circled nodes are deterministic nodes and represent the battlefield conditions that are known to the commander before making the decision. These nodes influence the decision and, along with the decision node, influence the commander's objectives, which are indicated by the hexagon-shaped value nodes.

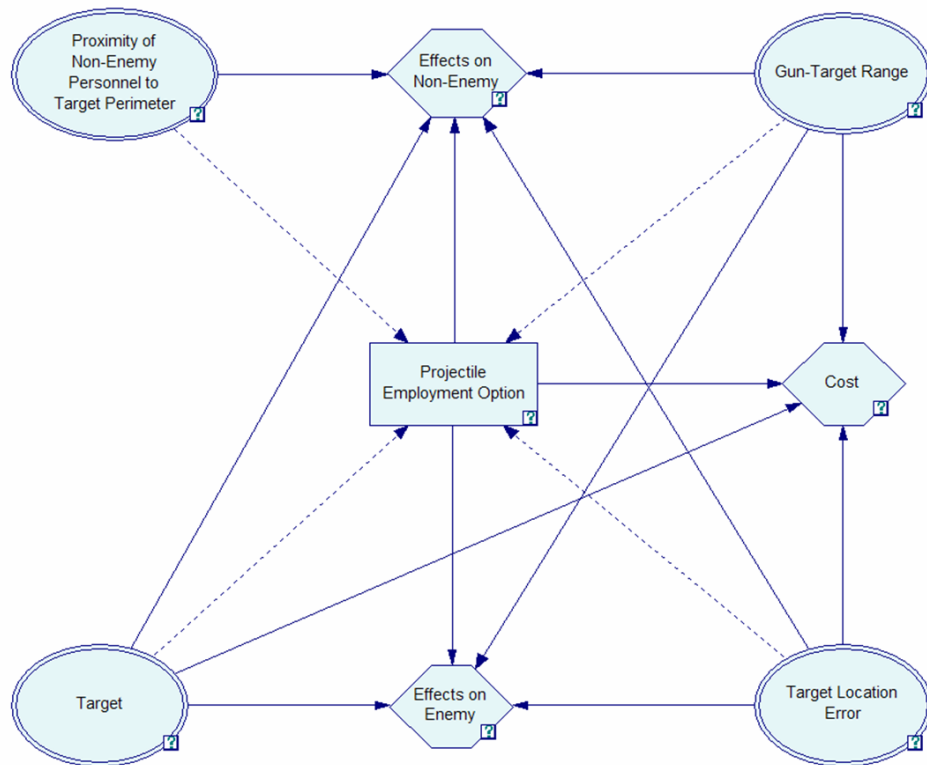


Figure 1. Influence Diagram Representing the Decision Problem

D. FIRES DEFINED

Before continuing, there must be a common understanding of the terms “precision fires” and “area fires”. The terms are not defined in Joint Publication 1-02, Department of Defense Dictionary of Military and Associated Terms or Army Field Manual 1-02, Operational Terms and Graphics. Army Field Manual 6-30, Observed Fire does refer to these terms as types of adjustment for conventional munitions. Intuitively, it is understood what is meant by these terms, but they are left to interpretation. “Area fires” is commonly used to compare against “precision fires”. Since we consider precision fires

to be “accurate fires”, this comparison often gives the impression that “area fires” must be “ineffective” or “inaccurate” fires. We will use the following definitions throughout this paper because of this ambiguity.

- *Precision fires* refer to fire missions that require one or more projectiles fired by one weapon system to achieve the desired effect on an *accurately* located *point* target.

- *Area fires* refer to fire missions that require more than one projectile fired by more than one weapon system to achieve a desired effect on a given *area* target or inaccurately located *point* target.

The obvious difference between the two types of fires is the type of target, not the type of munitions. Therefore, we must understand what the different types of targets are before discussing precision fires and area fires any further. It is also necessary to understand the different patterns of aim points used to achieve the desired effects on each type of target.

1. Target Types

The U.S. Field Artillery divides targets into four categories: Area (personnel), Area (materiel), Small (personnel), Small (materiel). The focus of this study is on personnel targets. Examples of Small (personnel) targets include observation posts, individual fighting positions, command posts, and squads. Examples of Area (personnel) targets are formations of personnel from the platoon-level and up. The size and shape of a formation depend on the number of personnel in the unit and the activity of the unit.

Target categories are further divided into types. The target types addressed in this study are point, linear, and circular targets. It is important to keep in mind that current U.S. Field Artillery doctrine is based on the use of conventional munitions. Therefore, some of the definitions and procedures do not seem prudent when using precision munitions.

The Field Artillery defines a *point target* as “a target area 200 meters or less in width and length. Minimum accuracy of the target location is [+/- 100 meters].” (FM 6-30, 1991) A *linear target* is one that is “more than 200 meters but normally less than 600 meters long... A linear target is designated by two grids or by a center grid, a length, and

an [orientation from North].” (FM 6-30, 1991) A *circular target* is one that is “in a circular pattern or is vague as to exact composition...it is designated by a center grid [coordinate] and radius greater than 100 meters.” (FM 6-30, 1991)

2. Sheafs

A sheaf is a pattern of aim points used to attack a target. The type of sheaf used depends on the type of target that the artillery unit is attacking. This study is only concerned with three sheafs. These sheafs are the converged sheaf for the point target, linear sheaf for the linear target, and circular sheaf for the circular target.

A *converged sheaf* is a pattern in which all weapons have the same aim point. A *linear sheaf* is described by a length and orientation or by two end-point grids. Aim points are evenly distributed about the target center along the length and orientation specified. The distance between aim points is determined by dividing the length of the target by the number of weapons firing. A *circular sheaf* is described by a center grid coordinate near the target center and a radius. Aim points are evenly distributed on a concentric circle half the radius of the circular target.

3. Precision Fires

The Field Artillery currently has two types of precision fire missions for conventional munitions; a *precision registration* mission and a *destruction* mission. For conventional munitions, precision fire procedures “by their nature, require high ammunition expenditure and make the firing unit vulnerable to enemy target acquisition.” (FM 6-30, 1991) Precision registration is used often to correct firing error of conventional munitions. Destruction missions are rarely used with conventional munitions.

Because of the amount of time and [conventional] ammunition required, destruction missions should be avoided. Only a target that is critical to an operation should be engaged in this manner, and only if no other means exists to destroy the target. (FM 6-30, 1991)

A destruction mission using conventional munitions involves one gun firing many rounds (projectiles) to destroy a point target (i.e. tank). An observer continually adjusts the fire of the gun until each impacting round is within a specified threshold distance (10-15 meters) around the target. Once the threshold is met, the observer directs the gun to

continue to fire additional rounds. After every one to three rounds, an additional refinement is made by the observer and firing is continued until the target is destroyed or the mission is ended. In contrast, a destruction mission using PGM would involve destroying the same tank with one cannon firing one laser-guided projectile.

Precision fire procedures place a great deal of responsibility on the observer because the adjusting point must be accurately located; usually to within 10 meters. This could involve several adjusting rounds depending on the observer's initial target location error (TLE). With an accurate observer, precision munitions can reduce the high ammunition expenditure of precision fires by reducing the number of adjustments and the number of misses produced by firing error.

4. Area Fires

The purpose of area fire is to cover the target area with dense fire so that the greatest possible effects on the target can be achieved. The type and amount of ammunition requested by the observer depend on the type of target, its posture, and its activity. (FM 6-30, 1991)

Area fire can be used for inaccurately located point targets as well as area targets. Consider a situation where we know that a point target is within a given area, but don't know exactly where in that area. The artillery can fire an area fire mission to saturate the area and ensure the point target is within the effects of the sheaf. This can be done with either type of projectile, conventional or precision.

Consider an example of a field artillery battery (6-8 guns) firing precision munitions in an area fire role. The battery fires on an area target (infantry company in the defense) using one of two methods. It can fire at aim points on accurately located sub-targets (personnel in fighting positions) or it can fire a sheaf that distributes effects on the target area.

These examples are meant to reinforce the point that the type of fires do not depend on the type of munitions. It depends on the target. Therefore, we must understand how to analyze a target in order to determine how to attack it.

E. TARGET ANALYSIS

The effects actually achieved on a target depend on several factors. These include target characteristics, target location, terrain and weather, and commander's attack

criteria. In order to compare the effects of precision vs. conventional munitions, we must understand what these factors are and how they influence a commander's decision of how to attack a target.

Target analysis is the examination and evaluation of an enemy target situation to determine the most suitable weapon, ammunition, and method required to defeat, neutralize, or otherwise disrupt, delay, or limit the enemy. Not only does target analysis involve determining the amount and type of ammunition required to inflict a given damage (or casualty) level on a particular target, it also involves a continuous process of consultation and cooperation between the commander and [his field artillery unit]. (FM 6-40 Appendix C, 1999)

In order to conduct target analysis, information must be known about the target, the environment, and the commander's desires. Figure 2 displays the information necessary to conduct target analysis.

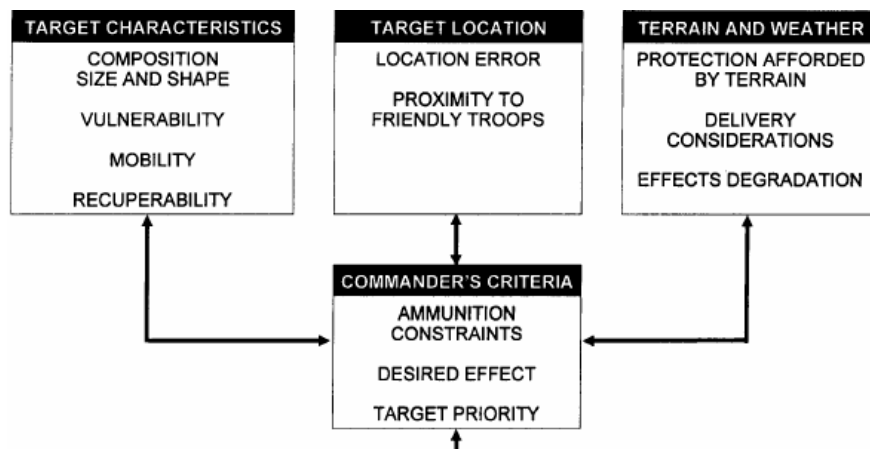


Figure 2. Elements of Target Analysis (from FM 6-40, 1999)

Target analysis has two results; the determination of the most suitable weapon-ammunition combination and the method of attack. Figure 3 depicts weapon-ammunition selection considerations.

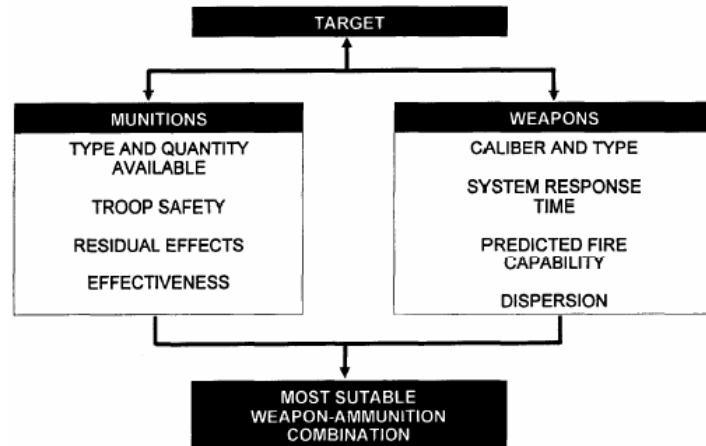


Figure 3. Weapon-Ammunition Selection (from FM 6-40, 1999)

Figure 4 depicts the considerations in selecting a method of attack. The method of attack includes the rate of fire, sheaf, method of control, number of volleys to fire, and type of trajectory (high angle or low angle).

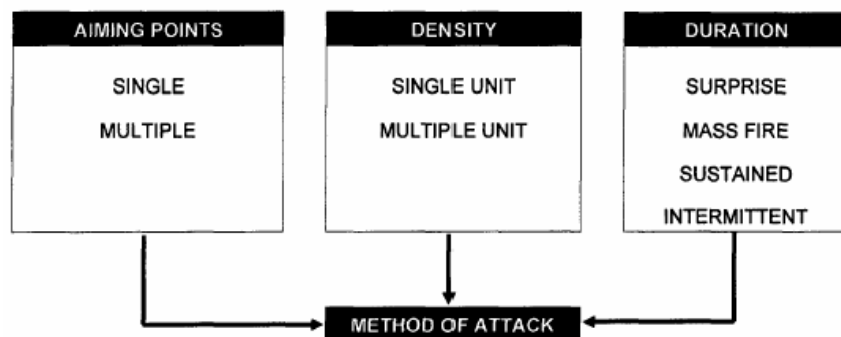


Figure 4. Considerations in Selecting Method of Attack (from FM 6-40, 1999)

FM 6-40, Appendix C contains a more complete discussion of target analysis. For now, we are mainly concerned with target characteristics and the commander's desired effects. Target location will be discussed later.

1. Target Characteristics

Information must be known about the target before firing the mission in order to achieve the desired effects. This information includes the type of target, size, shape, orientation, posture, mobility, and recuperability. This information can vary considerably for different targets. Therefore, the observer must describe the target as accurately as possible.

The target type, size, shape, and orientation were discussed earlier. The vulnerability and mobility of the target also depends on the type of target. Personnel are more vulnerable, and less mobile than tanks. Personnel vulnerability and mobility depend on terrain and posture.

For personnel targets in particular, the posture of the target is extremely important. Target postures normally used for personnel targets are standing, prone, and dug in. Information in weapons effects manuals is based on the assumption that personnel are wearing helmets and winter uniforms and that those in foxholes are in a crouching position...Normally, personnel targets will seek a more protective posture during an engagement (for example, from a standing to a prone position). The change is called posture sequencing. (FM 6-30, 1991)

The recuperability of the target involves how fast the target recovers from the effects of the artillery fire. For personnel targets, this usually involves replacement personnel as well as the medical treatment available. Assessing the recovery of personnel from artillery effects is very difficult to measure.

2. Commander's Desired Effects

A commander determines the level of effects required on a target in order for the unit to accomplish its mission. Effects are described by the terms *destruction*, *neutralization*, and *suppression*. Different techniques and expenditure of ammunition are required in order to achieve the desired effect. The challenge with using these terms is that they can be unclear and difficult to assess.

Destruction is defined as "a target out of action permanently, or 30 percent casualties or material damage" (FM 1-02, 2004). This effect requires the most ammunition and is the easiest to assess. To destroy an area target requires several units to fire a large expenditure of ammunition to produce near-direct hits on sub-targets (point targets). This is called massing fires. The amount of ammunition required depends on the size of the area target and the vulnerability (posture) of the sub-targets.

Neutralization of a target "knocks the target out of the battle temporarily. Casualties of 10 percent or more neutralize a unit. The unit is effective again when the casualties are replaced and/or damage is repaired." (FM 6-40, 1999) This effect is

achieved on an area target in the same manner as a destruction mission, but may require less artillery units and less ammunition.

Suppression is defined as the “temporary or transient degradation by an opposing force of the performance of a weapons system below the level needed to fulfill its mission objectives” (FM 1-02, 2004) This can be accomplished by firing continuously at a reasonably located target for a specified duration of time. It usually requires the least amount of ammunition to achieve this effect. The amount of ammunition depends highly on the size of the target and the duration of fire.

3. Battle Damage Assessment (BDA) of Targets

Effects depend on the target, the accuracy of the observer, accuracy and lethality of the weapon, terrain and weather, and the commander’s criteria. Evaluating whether the effects are achieved is very difficult and depends highly on the targets themselves as well as the evaluator. Effects on personnel are particularly difficult to measure because of human factors involved.

The most economical effects produced by cannons on an area target are suppression and neutralization. They are also more difficult to measure and more difficult to represent in simulations and training than the effects of destruction. There are several factors to consider before considering a target neutralized or suppressed. Many of those factors can be subjective.

To assess neutralization of area targets, we must determine whether or not the area target is temporarily out of action or 10 percent of its sub-targets (material or personnel) are neutralized (damaged/wounded) or destroyed (killed). The difficulty is in determining how much time is required to consider a target temporarily out of action. Another problem is determining what capability of the target must be damaged to consider it out of action. A person who is wounded in the leg may not be able to move, but can still shoot. A commander can suffer a broken leg from an airborne (parachute) drop and still be able to command if moved around the battlefield in a vehicle.

Suppression is the most difficult to measure and is unique for two reasons. First, it primarily affects personnel. Equipment is usually not suppressed directly, except when considering electronic warfare. The operators must be suppressed in order to suppress

the equipment. Second, it is time dependent. Once suppressed, a person can become unaffected after a certain period of time. Since each person is different, that period of time is a random variable.

The difficulty with assessing suppression of individual personnel arises from two unanswered questions. How close to an impacting artillery round does a person need to be in order to be suppressed? If suppressed, what is the duration of time a given individual remains suppressed if no other round impacts? The answers to these questions depend on several human and environmental factors, are highly subjective, and very little experimental data exists to support them. Reliable data is almost impossible without putting people's lives in danger.

A literature/data search was conducted, and a long history of interest in this subject was discovered, both in the United States and in the United Kingdom. In 1990, the U.S. Army Human Engineering Laboratory (HEL) published a two-volume report about this subject, which includes an historical perspective, a combat modeling perspective, a behavioral science perspective, and an experimental perspective. The U.S. Army Combat Developments Experimentation Command (CDEC) conducted a series of suppression experiments with live troops and live ammunition in the 1970s and published a report about the results. The data in that report constitute what appears to be the only large scale experimental suppression data collected since World War II. (Wald, 2000)

Suppression is too often ignored in training and in computer simulations because of the difficulty in realistically representing it. Artillery simulators do not provide the same physical and psychological effects as real artillery. The lack of a true threat can give an infantry soldier the confidence to rush an enemy trench line unhindered because the "fireworks" amuse him more than frighten him. During training exercises involving simulated artillery fire, large amounts of ammunition are expended with very little destroyed. This can give maneuver commanders the impression that artillery is ineffective. There is often no mention of suppression effects during after-action reviews unless smoke projectiles are used.

Regardless of the inability to accurately represent suppression in simulations and training, the suppressive effects of artillery are too important not to include in a study of artillery effectiveness. "It is quite reasonable to expect that the suppression effect of

superior firepower will frequently be greater than the attrition effect.” (Hughes, 1995) Therefore, this study uses suppression, as well as destruction and neutralization in order to determine the true measure of performance of each type of projectile.

4. First-Round Fire-For-Effect (FFE)

Artillery neutralizes or destroys a target most effectively when the first volley fired by an artillery unit is accurate enough to provide effects on target. This is called “First-Round FFE”. First-round FFE has always been a goal of the field artillery for this reason. Figure 5 illustrates the relationship between effectiveness and the number of adjustment rounds required for a fire mission.

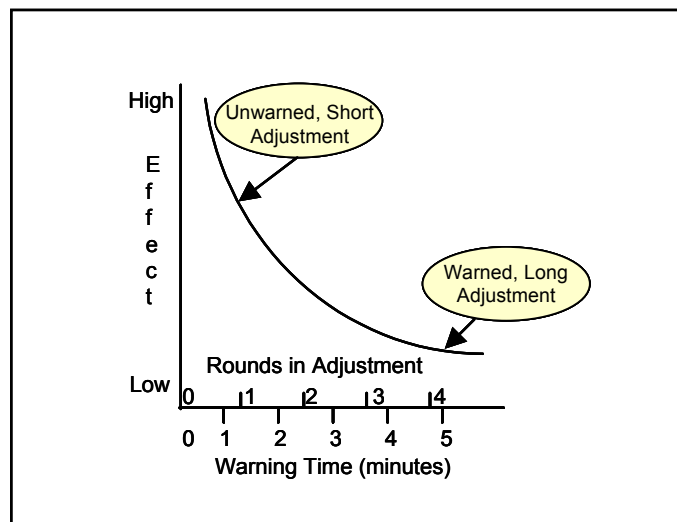


Figure 5. Relationship Between Effectiveness and Number of Adjustments (from FM 6-30, 1991)

To achieve accurate first-round fire for effect (FFE) on a target, an artillery unit must compensate for nonstandard conditions as completely as time and the tactical situation permit. There are five requirements for achieving accurate first-round fire for effect. These requirements are accurate target location and size [description], firing unit location, weapon and ammunition information, meteorological information, and computational procedures. If these requirements are met, the firing unit will be able to deliver accurate and timely fires in support of the ground-gaining arms. If the requirements for accurate predicted fire cannot be met completely, the firing unit may be required to use adjust-fire missions to engage targets. Adjust-fire missions can result in less effect on the target, increased ammunition expenditure, and greater possibility that the firing unit will be detected by hostile [target acquisition] assets. (FM 6-40, 1999)

We presume that precision-guided munitions would allow the artillery to achieve first-round FFE more readily than conventional munitions. Conventional munitions follow a ballistic trajectory that cannot be altered once the round leaves the cannon tube. Precision-guided munitions can adjust their path and do not have to follow a ballistic trajectory. They would increase effectiveness by requiring less adjustment rounds or none at all.

PGM have a distinct advantage in responsiveness as well as accuracy. An artillery firing unit can forgo many of the time-consuming steps required to meet four of the five requirements for accurate predicted fire. The only requirement that must be met is the “accurate target location and size description”. Therefore, an observer is required that can provide a small target location error (TLE) and accurate description of the target.

F. AREA FIRES AND SUPPRESSION

There are concerns about the use of area fires and suppression during combat operations because of the risk they pose to collateral damage and fratricide. “One inappropriate shot can greatly complicate and even alter a nation’s strategy.” (Lucas, 2002) The inherent risks, along with improvements of precision weapons, challenge the necessity for the use of area fires and suppression.

Some argue that because technology is providing precise intelligence, targeting and weapons, we don’t need area fire capabilities and the variety of ammunition effects that organic cannon and rocket artillery bring to the fight. They argue that precision will give us surgical one-shot/one-kill capabilities with target location so precise and situational awareness so complete that suppression won’t be necessary. (Barry, 2004, 13)

As long as maneuver forces are required to get close to and destroy an enemy, there will be a need for suppressive fires. Suppression provides protection and freedom of movement for the friendly maneuver forces by preventing the enemy from moving, shooting, observing, and/or communicating. The enemy is prevented from conducting these actions through a combination of physiological and psychological effects that the munitions have on them (fear of harm, loud explosions preventing clear communication) and the physical effects on their environment (dust and debris preventing observation).

Aircraft are often considered to be the preferred method for delivering ordnance onto a target. “Some argue that precision fires from the air are the best solution for

delivering fires and effects in support of the [Joint Force Commander's] full-spectrum operations.” (Emerson, et al, 2004, 8) They argue that a target can be destroyed by just one hit with a larger, aerial-delivered, precision-guided bomb than with artillery fire. This may be true in many situations, but not all.

Although we have the most powerful Air Force in the world, it still faces challenges with its ability to provide timely and effective fires. These challenges include bad weather, air-to-ground coordination, limited suppression effects, and limited ability to identify targets. Also, air-delivered missiles and bombs and the means to deliver them are usually more costly than most delivered by surface weapons.

Air Force or Naval Aircraft may not be available nor have the proper munitions when needed. Field Artillery is a day/night, all-weather capability that is responsive to the UA commander. Aircraft may not have someone on the ground properly trained or equipped with the proper communications equipment to guide them onto a target. Requesting and adjusting artillery fire is a common skill among all soldiers and marines. Suppression has a short duration after the impact of an explosive projectile. One 2000 lb bomb dropped from the air doesn't suppress as long as continuous artillery fire. The artillery can carry more ammunition, fire for longer durations of time, and shift its fire to other locations quickly.

During Operation Desert Storm, about 30% of the total Iraqi armor and artillery kills occurred during the 44-day air war with about 70% of the kills occurring during the 96-hour ground war. During the 1999 Operation Allied Force in Kosovo, the allied air forces planned 6,766 sorties, but 3766 were aborted due to weather. Of the 3,000 sorties actually flown, 990 were adversely affected by weather. More than 14,000 weapons were expended but less than 5% of the Serbian combat systems were destroyed by the 78-day air campaign. (Emerson, et al, 2004, 8)

Different targets require different weapon systems to provide the commander's desired effects. Either type of fires can be used. Currently, the artillery cannot conduct precision fires effectively. In order to stay relevant in the future, the artillery must have the flexibility to conduct both area and precision fires effectively. The introduction of the new precision-guided munitions (Excalibur, PGK, and G-MLRS) will enable them with that flexibility.

There is no doubt that precision munitions are best suited for precision fires. The question is, “When are PGM useful for area fires?” The usual response to that question is “Never! The monetary cost alone is too great and there is no guarantee that the effects would be significantly different.” This argument is very persuasive. However, we presume that a commander may want to use precision munitions in an area fire role to reduce the risk of fratricide, reduce the risk of collateral damage, and to maximize effects on targets with first-round fire-for-effect (FFE).

Improved accuracy of our weapons and ammunition should also enable us to reduce the volume of fire while improving effectiveness. Without the need to conduct a precision registration or to adjust rounds, ammunition expenditure can be reduced while effectiveness is increased. Therefore, the question to address is when to use precision munitions in an area fire role vs. conventional munitions.

G. METHODOLOGY

This study is meant to answer the previous question for the commander. We assume that a commander will require strict decision criteria to be met in order to use precision munitions for area fires because of the cost. Chapter 2 explores the decision criteria a commander would use to make a decision. It also explores the criteria’s relationship to each other. The criteria are combined to make one measure of effectiveness (MOE) to compare the two types of munitions.

Chapter 3 describes the simulation model used to determine the values of the criteria. It also describes the battlefield conditions (TLE, the Target, and GT Range) influencing them. Analysis is conducted in Chapter 4 to compare the two projectiles and determine how the battlefield conditions affect the decision criteria. Understanding how the conditions influence the criteria can assist with the decision.

A tactical decision aid is developed to compare the single MOE of both projectiles (Chapter 4). This will assist the UA commander in determining which type of ammunition to use for a given set of battlefield conditions. The optimal choice for the decision maximizes the effects on the enemy, minimizes the risk of non-enemy casualties, and minimizes the cost of munitions.

II. THE DECISION MODEL

A. THE SCENARIO

The combination of artillery firepower and infantry firepower destroys an enemy force more economically than either one alone. This synergistic relationship is the basis for the scenario that the decision model represents. The scenario involves an artillery platoon (4 guns) providing *close support* fires for a maneuvering friendly infantry unit that is attacking a stationary enemy infantry unit.

Close support fires are used to engage enemy troops, weapons, or positions that are threatening or can threaten the maneuver force. They allow the commander to rapidly multiply combat power and shift effects quickly about the battlefield. Close support fire ...erodes enemy forces, and inflicts damage well beyond direct fire ranges. (FM 3-09, 2001)

Close support artillery fire assists the infantry in two ways. First, it reduces enemy forces to manageable levels before the infantry unit engages them with their own weapons. This enables the friendly infantry to achieve superior firepower, which increases their chance of success when they assault the enemy. Second, close support fire protects the infantry by preventing the enemy from observing and firing on them. This decreases the number of casualties the infantry unit would suffer while moving.

The objective of the friendly infantry unit is to kill or capture the enemy unit. The friendly unit must occupy the enemy-held area in order to accomplish their objective. The primary difficulty with accomplishing this objective is moving to the area unobserved and unhindered by enemy fire. This is necessary in order to take advantage of surprise and to ensure their small arms weapons (rifles, machine guns, etc) are within range and in a position to be used effectively on the enemy.

The initial distance between the friendly and enemy is beyond small arms range. The friendly infantry require an artillery fire mission to allow them to move unhindered and unobserved toward the enemy. They need continuous artillery fire to ensure the enemy is suppressed. This results from the assumption that a single person is only suppressed for a few seconds after each impacting round. The duration of fire depends

on how long it takes for the friendly infantry to move to the enemy positions. Close support fire missions usually last between approximately three to five minutes.

The artillery stops firing when the infantry unit reaches the “Keep-Out” distance. If the friendly unit is within range of their small arms weapons, they will provide their own suppressive fire and continue the assault. If the artillery fire produces enough casualties, there will be little resistance by the enemy when the friendly force maneuvers onto the objective area.

The friendly force’s mission is complicated by civilian personnel in close proximity to the target. We assume our enemies know we are concerned about protecting civilians and structures. They position themselves in close proximity of civilians and inside protected structures in order to protect themselves. This has often been the case during Operation Iraqi Freedom where insurgents used mosques to stage operations and hide from American forces.

This scenario occurs in the near future. Precision munitions have been fielded to artillery units, but they are in short supply due to monetary cost and logistics constraints. Therefore, a commander requires certain criteria to be met before they are used.

B. THE DECISION CRITERIA

Recall the objectives of the commander.

1. Maximize the effects of fire on the enemy.
2. Minimize the effects of fire on non-enemy.
3. Minimize the cost of firing.

This study uses five criteria to represent the three objectives. We call them the fractional damage (FD), fractional suppression (FS), probability of non-enemy casualties $P_C(R)$, keep-out distance K , and cost. Fractional suppression and fractional damage are both used to represent the effects of fire on the enemy. Either $P_C(R)$ or K is used to represent the risk of non-enemy casualties.

1. Effects of Fire on the Enemy

a. Fractional Damage, FD

Fractional damage is the expected fraction of enemy personnel in the target area that are wounded or killed during an artillery fire mission.

$$FD = \frac{1}{N} E[W + K] \quad (1)$$

where W is the total number of personnel wounded at the end of a fire mission, K is the total number of enemy personnel killed at the end of a fire mission, and N is the total number of enemy personnel in the target area.

b. Fractional Suppression, FS

As mentioned earlier, artillery fires allow a friendly infantry unit to move toward an enemy force unhindered by enemy fire or observation. The only sure way for a commander to assess whether or not an enemy is suppressed is whether or not the enemy is firing at his unit. So the effort must be to prevent an enemy infantry unit from being able to fire on friendly infantry. Obviously, enemy who are killed or suppressed cannot fire on friendly forces. Wounded enemy, however, may still be dangerous. The term “suppression” in this criterion will be used to refer to the combined effects of killing and suppressing for these reasons.

We are particularly interested in the average fraction of personnel in the target area that are suppressed within a given time interval. The time interval, T , depends on the duration of artillery fire while the infantry are moving. Let K_t denote the number of enemy personnel killed at time t (seconds) and let S_t denote the number of enemy personnel suppressed at time t (seconds). The average fraction of enemy personnel unable to fire during a time interval, T (seconds), of one fire mission is

$$Y(T) = \frac{\int_{t=0}^T \left(\frac{S_t + K_t}{N} \right) dt}{T} = \frac{1}{NT} \int_{t=0}^T (S_t + K_t) dt \quad (2)$$

where N is the total number of enemy personnel in the target area.

Fractional Suppression (FS) is the *expected* average fraction of enemy suppressed during a fire mission.

$$FS = E[Y(T)] = \frac{1}{n} \sum_{i=1}^n Y_i(T) \quad (3)$$

where n is the number of repeated fire missions measured in a simulation.

2. Risk of Non-Enemy Casualties

We use the term *casualty* to represent both killed and wounded personnel. We combine killed and wounded together because we assume that wounded non-enemy personnel are equally as detrimental to a friendly unit's success as killed personnel. The loss of life, limb, or eyesight of a friendly combatant from a "friendly" weapon system causes the morale of a unit to suffer, which becomes a detriment to that unit's success. The death or injury of a civilian can also be severely damaging to the goals of military operations and national strategy. Suppression doesn't have the same impact because friendly or civilian personnel are not physically harmed.

We are concerned with non-enemy personnel in a "danger close" situation. "Danger close" indicates that friendly forces are in close proximity ($< 600\text{m}$) to the target center or the intended mean point of impact of munitions. Notice that this definition does not apply to civilian personnel. In fact, there are no explicit procedures identified in the current field artillery doctrine that are specifically designed to protect civilians. In this study, we assume that "danger close" does apply to civilians.

"Danger close" is simply a warning to both the maneuver commander and the artillery firing unit to take proper precautions. Risk-estimate distances are used in danger close situations to determine whether or not to fire. The field artillery defines *risk-estimate distances* as "the distance in meters from the intended center of impact at which a specific degree of risk and vulnerability will not be exceeded." (FM 3-09.21, 2001)

The U.S. Field Artillery currently uses the "5-minute assault criterion for a prone soldier in winter clothing and helmet" to determine the risk to friendly personnel. This criterion involves the probability of incapacitation $PI(R_I)$ of a person at a distance R_I from

the intended center of impact. The probability of incapacitation (PI) means that “a soldier is physically unable to function in an assault within a 5-minute period after an attack” (FM 3-09.21, 2001).

Table 1 is used to determine the risk distance, R_I , for different weapon systems at different ranges. For example, the value of R_I such that $PI(R_I) = 0.10$ for an M109 155mm howitzer firing at a target at maximum range is 125m. A problem with Table 1 is that no guidance is given to the commander about how to use this table, except that the “ground commander must accept risk when targets are inside 0.1 percent PI.” (FM 3-09.21, 2001)

Item/System	Description	Risk Estimate Distances (Meters)					
		10% PI			0.1% PI		
		1/3	2/3	Max Rg	1/3	2/3	Max Rg
M102/M119	105mm Howitzer	85	85	90	175	200	275
M109/M198	155mm Howitzer	100	100	125	200	280	450
M109/M198	155mm DPICM	150	180	200	280	300	475
M270A1	MLRS	2 km	2 km	2 km	2 km	2 km	2 km
M270A1	ATACMS	5 km	5 km	5 km	5 km	5 km	5 km

Table 1. Risk Estimate Distances in Current Use for 10% and 0.1% PI at 1/3, 2/3, and Maximum Range of the Weapon System (from FM 3-09.21, 2001)

There are issues with the “5-minute assault criterion”. It does not account for civilians and it uses the same risk distances for every situation. Civilians are usually less protected and often standing or walking. Using the same risk distances for every target limits the level of effects that can be achieved on a particular target. This may be a good “rule of thumb”, but different situations provide different risks and this rule of thumb may unnecessarily prevent the commander from maximizing effects on the enemy.

Lucas (2002) and David (2001) both address in their papers the challenge of maximizing the effect on a target “while simultaneously maintaining tolerable risk distances” (Lucas, 2002). There is a tradeoff that must occur between ensuring the safety of non-enemy personnel and not allowing the enemy to operate within safe havens. A commander must determine what level of risk to non-enemy personnel is acceptable in order to maximize effects on the enemy.

A problem with using a risk distance measured from the target center is that it does not accurately reflect the risk to non-enemy personnel. If the target is linear with a length of 300 meters, then a distance of 150m from the target center does not accurately reflect the risk unless the direction is known as well. Non-enemy personnel are in much greater risk when they are 150m from the center along the length of the target than if they are 150m in a direction perpendicular to the length of the target.

This study replaces PI and R_1 with two different criteria to represent the desire of the commander to minimize the risk of a non-enemy casualty during a fire mission. They are the probability of a non-enemy casualty, $P_C(R)$, and a risk estimate distance called the “Keep-Out” distance, K .

a. Probability of Non-Enemy Casualties, $P_C(R)$

$P_C(R)$ is the probability of a non-enemy casualty when non-enemy personnel are at a distance R from the perimeter of the target. The main difference between this probability and $PI(R_1)$ is in the risk distance used to compute the probability. This study uses the perimeter of the target to determine the values of R because each target has a different shape and size.

Commanders have a very grave concern for the safety of their own personnel as well as civilians. They are risk averse and the values of $P_C(R)$ that they are willing to accept in order to fire a mission will be low to reflect this. The PI s in Table 1 are 0.10 and 0.001. Therefore, $P_C(R)$ must be determined for each type of projectile under specific sets of conditions and for different values of R , where R is a continuous variable. The projectile that provides a lower probability of casualty for a set of conditions is preferred.

As mentioned earlier, there are no doctrinal artillery procedures to specifically protect civilians. The only procedure to protect friendly forces is to state, “Danger Close” in the request for fire. This does not tell the commander the distance or direction that friendly personnel are from the target perimeter. It only tells the commander that there are friendly personnel near the target (<600 meters). Therefore, the commander may never know the value of R and cannot determine $P_C(R)$.

b. Keep-Out Distance, K

If R is not known, then we can use the “Keep-Out” distance, K , to represent the risk of non-enemy casualties. It is defined as the distance, K , where $P_C(K) = 0.01$ for a standing person. We use a standing person because it represents a worst-case scenario for a commander who is risk averse. The worst-case scenario is a non-enemy person that is standing at a very short distance from where a round will impact. Using the standing posture makes sense because civilians do not expect to be attacked and friendly forces attacking a target are usually upright and moving. A projectile with a smaller value of K for a given set of conditions would be the preferred choice when considering risk.

3. Cost

The cost is determined by the controlled supply rate (CSR). The CSR is “the rate of ammunition consumption that can be supported, considering availability, facilities, and transportation. It is expressed in rounds per [tube] per day.” (FM 1-02, 2004) This rate is established by the higher unit commander.

The cost is considered to be the number of days required to recover from the amount of ammunition expended during a fire mission.

$$Cost = m / (n \times CSR) \quad (4)$$

where m denotes the total number of rounds fired by the firing unit and n denotes the number of guns (tubes) in the firing unit. For this study, $m = 48$ rounds + total number of adjustment rounds fired and $n = 4$ guns.

This cost is important because it affects the commander’s ability to successfully accomplish future operations. Again, we assumed that PGM will be in shorter supply than conventional munitions. The commander may foresee a need for PGM in follow-on operations and may not want to fire too many in the current operation.

The problem with this criterion is that the CSR is unknown until an operation begins. There is no historical data to support a reasonable CSR to use for the type of PGM we are studying since they have not yet been fielded. Studies are currently being

conducted to determine the proper mix of precision and conventional munitions to have in the U.S. Field Artillery's future inventory.

Principal Deputy Undersecretary of Defense (AT & L) Michael Wynne stated in a "Special Department of Defense Briefing on Future Technologies for Indirect Fires" on May 15, 2002 that the estimated cost for one Excalibur round would be approximately \$10,000 to \$25,000. In comparison, a newer conventional High-Explosive round costs approximately \$850. Therefore, we will assume that a reasonable CSR for conventional munitions would be 15-25 times the CSR for precision munitions.

C. THE MULTI-CRITERIA DECISION MODEL

We have defined five decision criteria. They determine the level at which a certain munitions employment option meets each of the commander's three objectives. They must be combined into one measure of effectiveness (MOE) to determine the level at which an option meets all three objectives, simultaneously. The problem is that the decision criteria all have different attribute scales. FS and FD are proportions, Cost is measured in days, $P_C(R)$ is a probability, and K is measured in meters.

Utility functions are developed for each criterion to overcome this problem. The functions measure the level of achievement of each criterion's corresponding objective. Weights are also determined to measure each criterion's level of importance to the commander relative to each other. Finally, the utility functions and weights are combined into a single additive utility function. This function represents an employment option's level of achievement of all three of the commander's objectives.

1. Utility Functions

The values of the utility functions will range from zero to one. The alternative with the greatest utility value is the most preferred. Tables provide the reasoning behind the choice of utility functions for each criterion. They contain definitions that allow a commander to easily understand the tactical implications of the values of the criteria.

a. Fractional Suppression, FS

Table 2 provides the reasoning for the utility function for FS. There are five levels that range from very low fraction of suppression to very high. They are distinguished by the amount of freedom of movement afforded to the friendly infantry. The goal is to suppress as much of the target as possible in order to provide freedom of

movement to the friendly infantry force. Therefore, a commander would place more importance on higher values of FS.

Description	Values
Very High. The greatest amount of suppression on the target as possible. Allows friendly infantry maximum freedom of movement without fear of being fired upon by the enemy.	$FS \geq 0.90$
High. High degree of suppression. Friendly infantry have freedom of movement, but move cautiously.	$0.75 \leq FS < 0.90$
Medium. Adequate suppression. Allows the friendly infantry to move, but enemy may hinder movement.	$0.50 \leq FS < 0.75$
Low. Inadequate suppression. Friendly infantry must use other assets to augment the suppression. Must use bounding movement techniques. Enemy will severely hinder movement.	$0.25 \leq FS < 0.50$
Very Low. Marginal suppression. Friendly infantry must find alternate means to assault the enemy or abort the mission. Enemy prevents any movement.	$FS < 0.25$

Table 2. Fractional Suppression Attribute Scale

A commander would also place more importance on increases in FS at higher levels because they are considered to have greater tactical benefit than increases at lower levels. When we consider a three-person target, 80% is 2.4 people. That is, in effect, the entire target. A 5% increase yields 2.55 personnel. This is almost a guarantee that the entire target will be suppressed. When we consider a 126-personnel company-size target, 80% is 100.8. This isn't quite the entire target, but enough of the target would still be suppressed to allow the infantry to reasonably move freely. A 5% increase yields 107.1 personnel. An additional 7 people suppressed leaves only approximately 19 personnel available to fire on friendly forces. This is a very favorable position for the friendly infantry.

A commander would not consider increases at lower levels of FS to have significant tactical benefit. When we consider 10% suppressed, only 0.3 personnel of the three-person target and 12.6 personnel of the company-size target are suppressed. The rest of the enemy can still provide a significant threat to the moving friendly infantry. A 5% increase would yield 0.45 personnel of the 3-person target and 18.9 personnel of the

126-person target suppressed. There are still plenty of enemy personnel available on both targets to provide a significant threat.

The example above also suggests that larger targets require greater values of FS. This also supports the theory that a commander would place more importance on increases at higher values of FS. The following utility function provides a good representation of this preference.

$$U(FS) = FS^2 \quad (5)$$

Graphically, the utility function is shown in Figure 6.

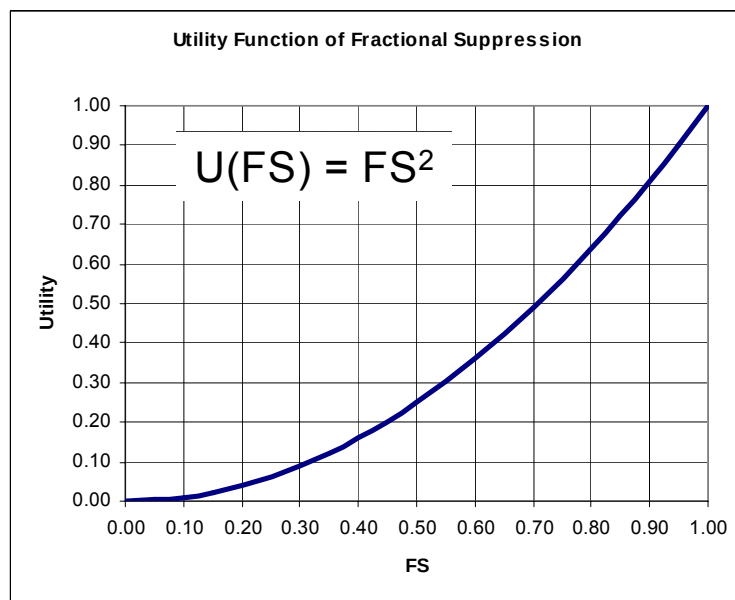


Figure 6. Utility Function of Fractional Suppression

b. Fractional Damage, FD

FD represents the amount of attrition that the enemy target suffers as a result of a fire mission. The scale in Table 3 should be familiar to a tactical commander. It is based on the definitions already used for neutralization and destruction. The levels are distinguished by the amount of enemy personnel in the target area after the fire mission that could still fight the attacking friendly infantry unit.

Description	Values
Very High. Annihilation. The friendly infantry will face little to no resistance when they begin their assault on the target. Negligible friendly casualties.	$FD \geq 0.70$
High. Destruction. The friendly infantry will face little resistance when they begin their assault on the target. Friendly infantry have superior combat power. Marginal friendly casualties.	$0.30 \leq FD < 0.70$
Medium. Neutralization. The friendly infantry will face resistance when they begin their assault on the target. Can gain superior combat power through fire and maneuver. Minimal friendly casualties.	$0.10 \leq FD < 0.30$
Low. Harassment. The friendly infantry will face significant resistance when they begin their assault on the target. Significant friendly casualties.	$0.05 \leq FD < 0.10$
Very Low. Nuisance. The friendly infantry will face heavy resistance when they begin their assault on the target...Severe friendly casualties.	$FD < 0.05$

Table 3. Fractional Damage Attribute Scale

Artillery fire rarely produces a high number of casualties on a target. The attrition effect of artillery is significantly less than the suppressive effect. Casualties above 30% are good, but the target is already considered effectively destroyed. Seventy percent casualties would leave very few enemy personnel capable of posing a serious threat to the friendly force, but higher percentages could be considered overkill.

A single casualty is better than none at all. More casualties are better. Therefore, a commander would place more importance on increases in casualties at lower values. The exponential utility function reflects this.

$$U(FD) = 1 - e^{\frac{-FD}{RT}} \quad (6)$$

where RT is the *Risk Tolerance* of the commander (Figure 7).

The risk tolerance determines how risk averse the utility function is. Smaller values of RT mean that the commander is more risk averse. In other words, the RT value represents the least value that a commander would be most comfortable with. For this study, let $RT = 0.30$, the FD value between Medium and High in Table 3.

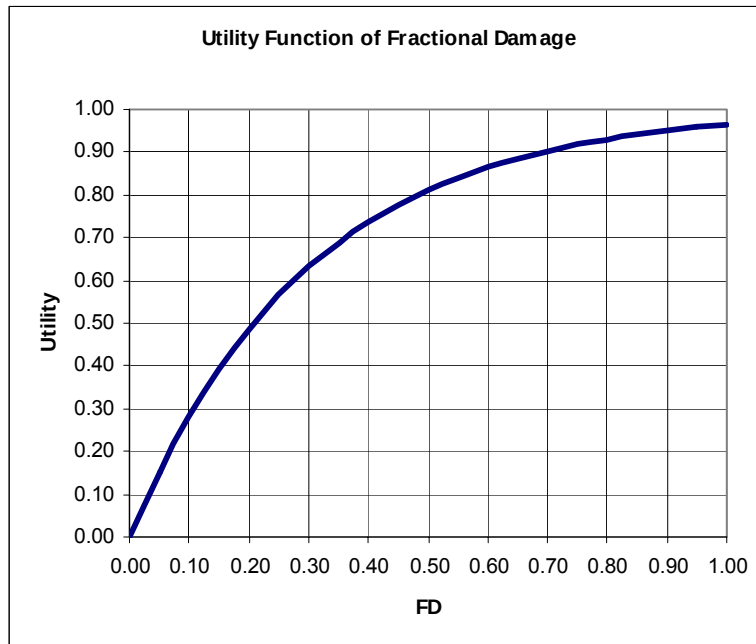


Figure 7. Utility Function for Fractional Damage.

c. Risk

The military risk management process is used to determine the utility functions for $P_C(R)$ and K . This method is familiar to commanders because it is an integral part of the military decision making process that all commanders are trained to use.

Risk management is a process that assists decision makers in reducing or offsetting risk (by systematically identifying, assessing, and controlling risk arising from operational factors) and making decisions that weigh risks against mission benefits. Risk is an expression of a possible loss or negative mission impact stated in terms of probability and severity. (FM 3-100.12, 2001)

The mission benefits, in this case, are the effects on enemy. The risk is the probability and severity of non-enemy casualties. A commander subjectively assesses the probability that non-enemy casualties will occur during a mission and the severity of the negative impact this event would have on the mission's success. The commander assesses the level of risk by combining these assessments into a "Risk Assessment Matrix" in FM 3-100.12, Multiservice Tactics, Techniques, and Procedures for Risk Management, (2001).

Tables 4 and 5 correspond with the probability categories used in the risk assessment matrix. Weights will be used to represent the commander's assessment of severity. The tables reflect a commander's aversion to the risk of non-enemy casualties. Any non-enemy casualty can be considered unacceptable. The tables capture that attitude.

Probability Categories	Values
Unlikely. Occurrence not impossible, but may assume will not occur during a specific mission or operation. Occurs very rarely, but not impossible.	$P_C(R) < 0.001$
Seldom. Remotely possible, but not expected to occur during a specific mission or operation. Occurs rarely within exposed population as isolated incidents.	$0.001 \leq P_C(R) < 0.05$
Occasional. May occur during a specific mission or operation, but not often. Occurs sporadically (irregularly, sparsely, or sometimes).	$0.05 \leq P_C(R) < 0.10$
Likely. Expected to occur during a specific mission or operation. Occurs at a high rate, but experienced intermittently.	$0.10 \leq P_C(R) < 0.30$
Frequent. Expected to occur several times or continuously during a specific mission or operation.	$P_C(R) \geq 0.30$

Table 4. Probability of Non-Enemy Casualty, $P_C(R)$, Attribute Scale

Relatively low probabilities of non-enemy casualties could produce very high risk. The utility function for $P_C(R)$ is

$$U(P_C(R)) = e^{\frac{-P_C(R)}{RT}} \quad (7)$$

where $RT = 0.05$, the value of $P_C(R)$ between seldom and occasional likelihood of occurrence.

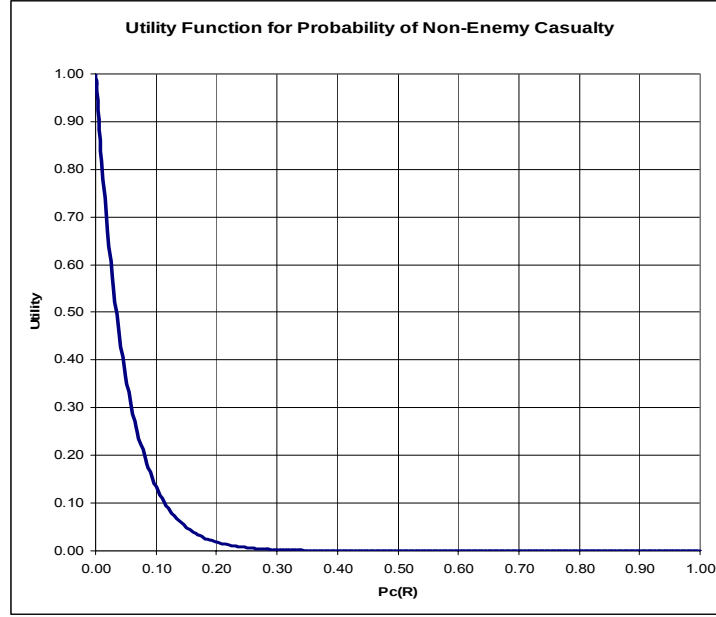


Figure 8. Utility Function of $P_C(R)$

Description	Values (meters)
Unlikely. Occurrence not impossible, but may assume will not occur during a specific mission or operation. Occurs very rarely, but not impossible.	$K < 25$
Seldom. Remotely possible, but not expected to occur during a specific mission or operation. Occurs rarely within exposed population as isolated incidents.	$25 \leq K < 50$
Occasional. May occur during a specific mission or operation, but not often. Occurs sporadically (irregularly, sparsely, or sometimes).	$50 \leq K < 100$
Likely. Expected to occur during a specific mission or operation. Occurs at a high rate, but experienced intermittently.	$100 \leq K < 200$
Frequent. Expected to occur several times or continuously during a specific mission or operation.	$K \geq 200$

Table 5. Keep-Out Distance, K , Attribute Scale

Again, Keep-Out Distance, K , is used when non-enemy personnel are danger close, but the distance R is unknown. A large “Keep-Out” distance is very undesirable. When K is less than 50, personnel have a very small chance ($P_C(R) < 0.01$) of becoming a casualty when outside of that distance (i.e. $R > K$). It is unlikely that non-enemy personnel would be within 50 meters of the target perimeter. On the other hand, it would be more likely that personnel within 600 meters of the target center would also be within 200 meters of the target perimeter, especially for large targets.

The utility function for K is

$$U(K) = e^{\frac{-K}{RT}} \quad (8)$$

where $RT = 50$ meters, the value of K between seldom and occasional likelihood of occurrence.

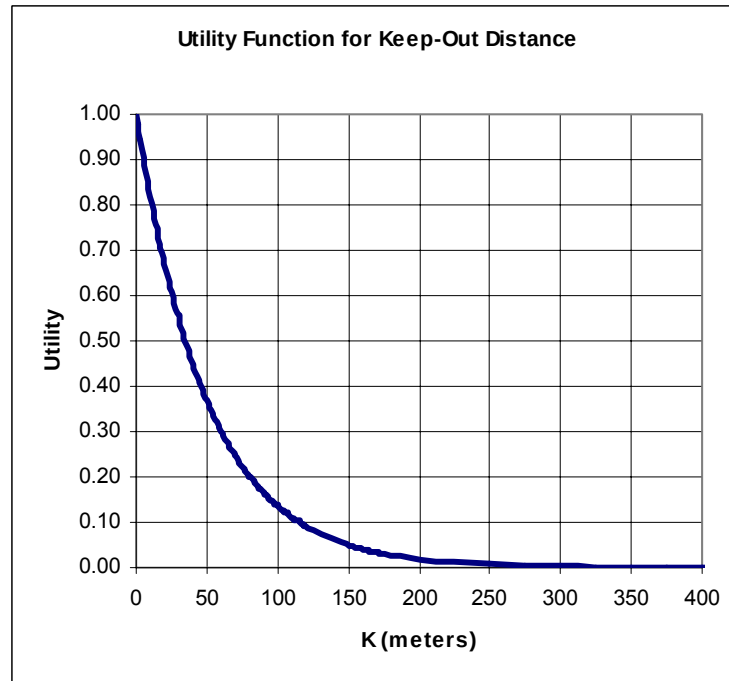


Figure 9. Utility Function of K

d. Cost

The scale used for cost was developed to correspond with the required supply rate (RSR) calculation procedure in FM 3-09.21, chapter 7. The RSR is the artillery unit's estimate of the amount of ammunition it will require for an operation. The RSR is sent from the artillery unit to the next higher headquarters. The higher headquarters determines how much of the RSR can be supported by facilities and transportation assets and reports that amount to the field artillery unit in the form of the CSR.

Description	Values (days)
Very Low. First day of Operation. Enough ammunition will be available to replace ammunition within one day.	$\text{Cost} \leq 1$
Low. Succeeding days. Enough ammunition will be available to continue fighting for a short period of time.	$1 < \text{Cost} \leq 5$
Medium. Transition. Ammunition may be too low to continue operations.	$5 < \text{Cost} \leq 10$
High. Protracted days. Ammunition will not be available if the operation is protracted over several days.	$10 < \text{Cost} \leq 15$
Very High. Combat ineffective. Ammunition is unavailable to provide support, indefinitely	$\text{Cost} > 15$

Table 6. Cost Attribute Scale

Cost depends on how the commander visualizes future operations. If the CSR is low, we consider the cost of firing to be high. There are two situations that may cause someone to argue that a low CSR does not necessarily mean a high cost. First, if there is plenty of ammunition on hand, the current stock may offset the cost for a few days. Second, the commander may consider that the operation may last just a few hours. If the required ammunition for the operation is already on hand, expending a large amount of ammunition and requiring several days to re-supply is not an issue.

These are valid arguments, but there are several counter-arguments. An artillery unit is limited in the amount of ammunition it can carry. Therefore, the current inventory of munitions may not be enough. Combat is also unpredictable. The supply on-hand can be used at a faster or slower rate than expected. In the recent Battle of Fallujah, “The biggest challenge we had was ammunition resupply. The amount of munitions expended was surprising, and we had to struggle to keep our cannons and [mortar] tubes supplied.” (Cobb et. al., 2005, p. 26)

It is better to have than to have not in combat. This study assumes that a commander has just enough ammunition for the current operation. We also assume that the commander has a follow-on operation after the completion of the current operation. Therefore, the commander wants to conserve the stock of ammunition on-hand so that it

is available for future operations. A utility function (Figure 10) that reflects this is

$$U(Cost) = e^{\frac{-Cost}{RT}} \quad (9)$$

where $RT = 5$ days, the value of Cost between low and medium.

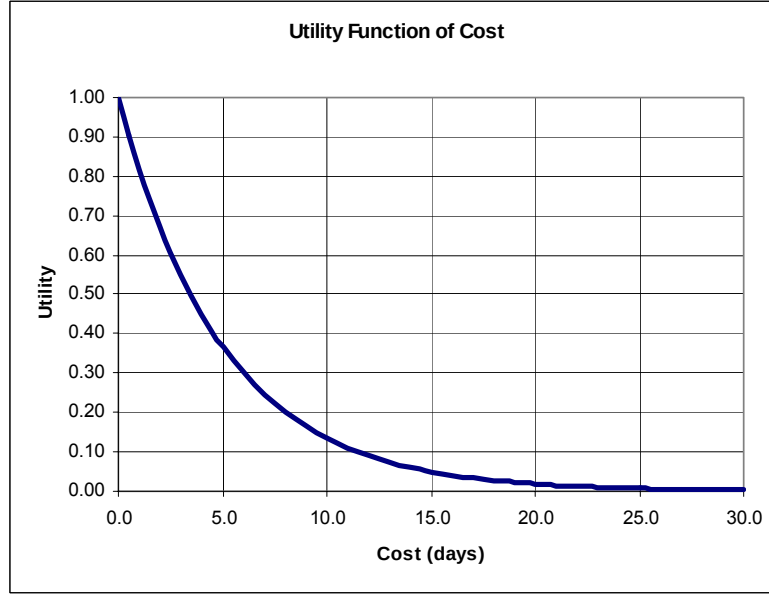


Figure 10. Utility Function of Cost

2. The Overall Decision Criterion

The utility functions of the decision criteria are now combined into a single additive utility function. The value of this utility function represents the overall consequence of a commander's decision of projectile employment option. It will also have a scale from zero to one where the option with the higher value is preferred.

The additive utility function is

$$U(FS, FD, Risk, Cost) = w_1 \cdot U(FS) + w_2 \cdot U(FD) + w_3 \cdot U(Risk) + w_4 \cdot U(Cost) \quad (10)$$

where "Risk" represents either $P_C(R)$ or K , $0 \leq w_i \leq 1$, $\forall i = 1, 2, 3, 4$, and $\sum_{i=1}^4 w_i = 1$. The weights w_1 , w_2 , w_3 , and w_4 represent the relative importance to a commander of each decision criterion for a particular operation.

Determining the weights is difficult. How important is one decision criterion relative to the others? The whole purpose of a fire mission is to attack a target and

achieve the desired effects. FS and FD are the intended effects of the fire mission and, presumably the most important. Risk and Cost are the unintended effects. However, a commander may consider Risk and Cost to be more important under certain situations.

3. Weighting the Decision Criteria

A commander is responsible for approving each fire mission request. However, a commander is usually not available to decide on which type of projectile to use for every fire mission request received during a battle. A commander delegates that task to a fire support officer (FSO). The commander provides guidance to his FSO, before the battle, to ensure that the FSO makes decisions in accordance with the commander's intent.

A commander doesn't provide guidance in the form of weights and does not have time available to determine appropriate weights. An FSO must be able to take the commander's guidance and convert it into weights. The FSO must then be able to explain to the commander what impact these weights have on the operation in terms that the commander can easily understand.

A commander's guidance can be very broad or very specific. This poses a problem to an FSO who has very little time to develop a plan to attack targets with field artillery. "Rules of thumb" would help an FSO to easily choose weights that meet the commander's intent and also allow some flexibility to choose weights that make good tactical sense.

a. Weights for Effects on Enemy

FS and FD both represent the same fundamental objective of the commander. The challenge is for the FSO to determine appropriate weights for these criteria based on the commander's desired effects on the target. If w_1 is large, then the commander strongly desires to suppress the target. If $w_1 = 0$, then the commander is only interested in attrition.

The commander's guidance provides the FSO with doctrinally stated tasks and purposes. A task describes a targeting effect against a specific enemy formation's function or capability that could interfere with the achievement of friendly objectives. The purpose describes how this effect contributes to accomplishing the mission within the commander's intent.

We will use five targeting objective terms to determine values for w_1 and w_2 , the weights associated with FS and FD. These terms are found in the tactical tasks stated by the commander in his guidance and defined in FM 3-09.4, Date Pending, and FM 3-90, 2001. They include *limit*, *disrupt*, *delay*, *divert*, and *damage*. They are used to describe the effects of attack on the enemy capabilities and should not be confused with the terms suppress, neutralize, or destroy, defined earlier.

Table 7 provides a recommended relationship between w_1 and w_2 that can be used by the FSO to determine appropriate values for them.

Tactical Task	Weights (FS vs. FD)
Limit. To restrict the enemy's capability to pursue a particular course of action (COA) or reduce the options and COAs available to the enemy commander.	$w_1 \geq w_2$
Disrupt. To break apart, disturb, or interrupt an enemy function. Disruption precludes the effective interaction or cohesion of enemy combat or combat support systems.	$w_1 > w_2$
Delay. To alter the time of arrival of forces at a point on the battlefield or the ability of the enemy to project combat power from a point on the battlefield. A form of retrograde in which a force under pressure trades space for time by slowing the enemy's momentum and inflicting maximum damage on the enemy without, in principle, becoming decisively engaged.	$w_1 < w_2$
Divert. To force an enemy to alter a particular COA once he is already in the execution phase.	$w_1 \leq w_2$
Damage. To inflict or cause damage to an enemy force, equipment, or capability or to an object or facility (such as a building, highway, airfield, railroad)	$w_1 = 0$

Table 7. Comparison of Weights for FS vs. FD.

Based on the definitions in Table 7, we can intuitively determine that limit, disrupt, delay, and divert will require a combination of suppression, neutralization, and destruction effects. Divert and delay will require more neutralization and destruction than suppression. Damage only requires neutralization and destruction effects.

b. Weights for Risk

The military risk management process is used to determine the value of w_3 , the weight for Risk. This weight represents how a commander views the "severity" of consequences if a fire mission causes non-enemy casualties. The definitions of "Risk Severity Categories" in Table 8 are from FM 3-100.12, Table A-D-1, 2001.

Risk Severity Categories	Weights Risk vs. FS & FD
Catastrophic. Loss of ability to accomplish the mission or mission failure. Death or permanent disability. Loss of major or mission-critical friendly system or equipment. Major civilian property (facility) damage. Severe environmental damage. Unacceptable collateral damage.	$w_3 \gg w_1, w_2$
Critical. Significantly degraded mission capability or unit readiness. Non-enemy injury causing disability. Extensive damage to friendly equipment or systems. Significant damage to civilian property or the environment. Significant collateral damage.	$w_3 \geq w_1, w_2$
Marginal. Degraded mission capability or unit readiness. Minor damage to friendly equipment or systems, civilian property, or the environment. Injury of non-enemy personnel.	$w_3 \leq w_1, w_2$
Negligible. Little or no adverse impact on mission capability. First aid or minor medical treatment. Slight friendly equipment or system damage, but fully functional and serviceable. Little or no civilian property or environmental damage.	$w_3 \ll w_1, w_2$

Table 8. Risk Severity Categories (from FM 3-100.12, 2001) and Comparison of Weights for Risk vs. FS and FD

c. Weights for Cost

The weight w_4 represents the importance of cost to the commander. Again, this depends on the commander's anticipated needs for future operations. Therefore, it depends on the type of current operation and level of operation. The type and level of operation are good indicators of the ammunition expenditure rate for that operation.

The type of operation includes stability, defensive, and offensive. Historically, defensive operations require the most ammunition and stability operations require the least amount. The level of operation includes high intensity, medium intensity, and low intensity. Historically, high intensity operations require the most ammunition and low intensity requires the least. Table 9 represents a comparison of weights depending on the operation.

Type of Operation	Intensity Level of Operation	Weights (Cost vs. FS & FD)
Defensive	High	$w_4 \gg w_1, w_2$
	Medium	$w_4 > w_1, w_2$
	Low	$w_4 \geq w_1, w_2$
Offensive	High	$w_4 \geq w_1, w_2$
	Medium	$w_4 \cong w_1, w_2$
	Low	$w_4 \leq w_1, w_2$
Stability	High	$w_4 \leq w_1, w_2$
	Medium	$w_4 < w_1, w_2$
	Low	$w_4 \ll w_1, w_2$

Table 9. Comparison of Weights for Cost vs. FS and FD.

d. Determining Weights Using the Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) (Saaty, 1982) is used to determine the weights. This process involves pair-wise comparisons of the decision criteria. The comparison guidelines in Tables 7, 8, and 9 are used with the scale in Table 10 to determine how much a commander would prefer one criterion over the other.

Intensity of Preference	Definition
1	Equally preferred. Two criteria contribute equally to an alternative.
2	Equally to moderately preferred
3	Moderately preferred. Experience and judgment slightly favor one criterion over the other.
4	Moderately to strongly preferred.
5	Strongly preferred. Experience and judgment strongly favor one criterion over the other.
6	Strongly to very strongly preferred.
7	Very strongly preferred. A criterion is strongly favored and its dominance is demonstrated in practice.
8	Very to extremely strongly preferred.
9	Extremely strongly preferred. The evidence favoring one criterion over another is of the highest possible order of affirmation.

Table 10. Pair-Wise Comparison Scale of Decision Criteria (from Gass, 1985)

A pair-wise comparison matrix is used to record the preferences for the FSO. Each criterion is equally preferred to itself, so the diagonals of the matrix are one. We indicate how much less a criterion is preferred by using the reciprocal of the intensity values in the first column of Table 10. Therefore, it is only necessary to fill out the upper triangle of the pair-wise comparison matrix with the values $1/9, 1/8, \dots, 1/2, 1, 2, \dots, 8, 9$.

Criteria	FS	FD	Risk	Cost
FS	1	I_{12}	I_{13}	I_{14}
FD	$1/I_{12}$	1	I_{23}	I_{24}
Risk	$1/I_{13}$	$1/I_{23}$	1	I_{34}
Cost	$1/I_{14}$	$1/I_{24}$	$1/I_{34}$	1

Table 11. Pair-Wise Comparison Matrix (I_{ij} = Intensity of Preference of Criterion i over Criterion j)

We use the geometric mean method (Gass, 1985) to compute the weights. First, calculate the product of the ratios of each row i and denote it Π_i . Calculate the corresponding geometric mean $P_i = \sqrt[4]{\Pi_i}$ for the four rows. Let $P = \sum_{i=1}^4 P_i$. The weight for each criterion is determined by computing $w_i = \frac{P_i}{P}$, $\forall i = 1, 2, 3, 4$.

Criteria	FS	FD	Risk	Cost	Π_i	$P_i = \sqrt[4]{\Pi_i}$	$w_i = \frac{P_i}{P}$
FS	I_{11}	I_{12}	I_{13}	I_{14}	$\Pi_1 = \prod_{j=1}^4 I_{1,j}$	$P_1 = \sqrt[4]{\Pi_1}$	$w_1 = \frac{P_1}{P}$
FD	I_{21}	I_{22}	I_{23}	I_{24}	$\Pi_2 = \prod_{j=1}^4 I_{2,j}$	$P_2 = \sqrt[4]{\Pi_2}$	$w_2 = \frac{P_2}{P}$
Risk	I_{31}	I_{32}	I_{33}	I_{34}	$\Pi_3 = \prod_{j=1}^4 I_{3,j}$	$P_3 = \sqrt[4]{\Pi_3}$	$w_3 = \frac{P_3}{P}$
Cost	I_{41}	I_{42}	I_{43}	I_{44}	$\Pi_4 = \prod_{j=1}^4 I_{4,j}$	$P_4 = \sqrt[4]{\Pi_4}$	$w_4 = \frac{P_4}{P}$
						$P = \sum_{i=1}^4 P_i$	

Table 12. Method of Computing Weights from the Pair-wise Comparison Matrix Using the Geometric Mean

A Consistency Ratio (CR) is determined (Render, et. al., 2003) to ensure that the preferences we choose in the pair-wise comparison matrix are consistent and follow the transitivity rule. The transitivity rule means that if criterion 1 is preferred to criterion 2 and criterion 2 is preferred to criterion 3, then criterion 1 is preferred to criterion 3. An example of an inconsistent matrix is one in which the preference of FS over FD is 4, the preference of FS over Risk is $\frac{1}{2}$, but the preference of FD over Risk is 2. The preference of FD over Risk should be less than $\frac{1}{2}$, which is the preference of FS over Risk.

A higher consistency ratio means we are less consistent. A lower ratio means that we are more consistent. In general, if the consistency ratio is 0.1 or less, the FSO's comparisons are relatively consistent. For a consistency ratio greater than 0.1, the FSO should seriously reconsider the preferences in the pair-wise comparison.

Utility functions for the decision criteria are created. An overall utility function for the decision is created. A method for determining weights is provided. The values of our decision criteria for given sets of battlefield conditions (TLE, Target Description, GT Range) are yet to be determined. We turn to a Monte Carlo simulation to determine these values.

III. THE SIMULATION MODEL

The simulation model used for this study is the Mortar Mission Model (MMM). The MMM was developed by the U. S. Army Research Laboratory at Aberdeen Proving Ground, Maryland. This model was developed to study the effectiveness of mortars and has been modified to represent the effects of 155mm High-Explosive (HE)/Point Detonating (PD) rounds.

The Mortar Mission Model is a Monte Carlo model that simulates the lethality and suppression of a mortar mission against an infantry unit that remains stationary for the duration of the mortar mission. It includes fire observation and adjustment, followed by fire for effect. It also includes changes in posture of the infantry in response to the mortar fire. The output of the model includes a time history of suppression as well as the cumulative attrition of the defending force. (Wald, 1999)

A. ELEMENTS OF THE SIMULATION MODEL

The model can best be described by the following elements: the observer, the fire mission, the weapon system, the ammunition, and the area target.

1. The Observer (Sensor)

Field Artillery weapons are indirect fire weapons. This means that the weapon system cannot see the target itself and must rely on a forward observer to locate targets and adjust the field artillery fire in order to obtain the desired effects. The observer's accuracy depends on the experience and training level of the observer, the equipment used, and the precision of the grid coordinates being used.

The accuracy of the observer has a circular normal distribution (Figure 11) with mean at an *adjusting point*. In area fire missions, the adjusting point will be a well-defined point near the center of the target area. The standard deviation of the range, σ_R , (distance parallel to the observer-target (OT) line) and the standard deviation of the deflection, σ_D , (distance perpendicular to the OT line) are considered to be equal, $\sigma_R = \sigma_D = \sigma$. The observer's accuracy is measured by the Target Location Error (TLE). TLE represents the circular error probable (CEP) of the observer's initial estimate of the adjusting point location. It causes the aim point of the firing unit to be offset from the adjusting point (Figure 11).

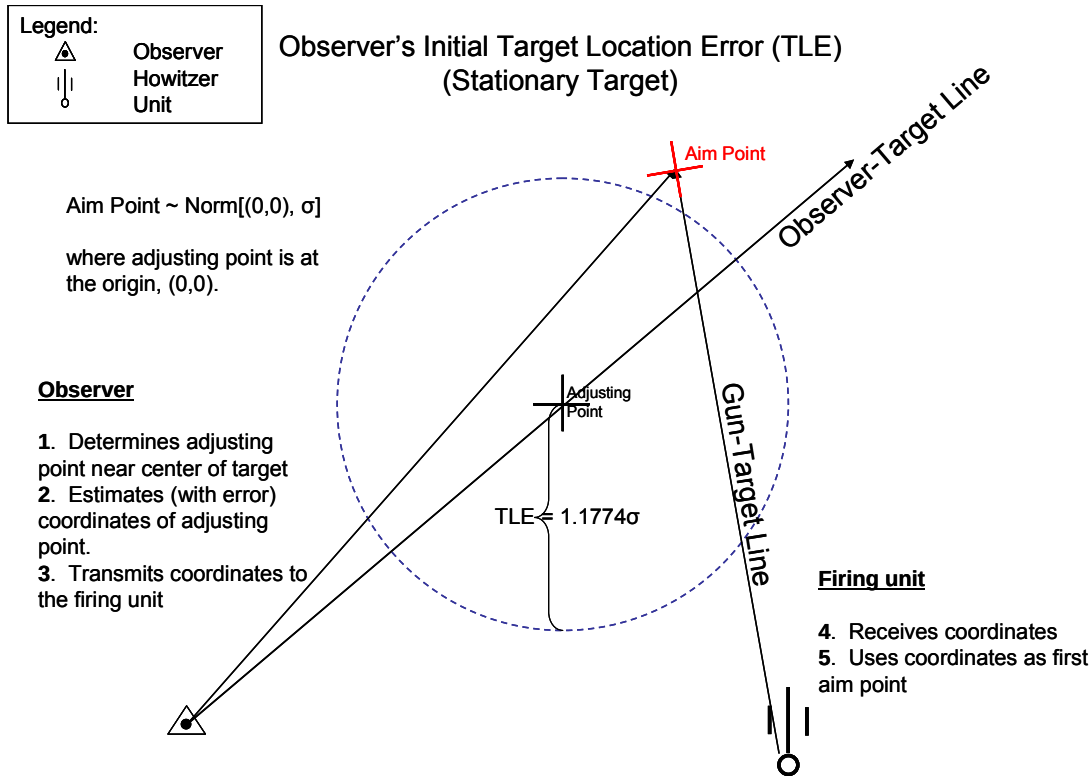


Figure 11. Representation of the Observer's Target Location Error (TLE)

2. The Fire Mission

The observer usually determines the type of mission to fire and the adjustment technique to use. The observer sometimes determines the method of controlling the firing of the guns. This is usually determined by the artillery platoon headquarters.

a. Type of Mission

There are different types of fire missions. The primary mission of this model is the adjust fire mission. An adjust fire mission is considered to have two phases, an "adjustment" phase followed by a "FFE" phase. During the adjustment phase, the observer will select an *adjusting point* (Figure 11). The firing unit will fire one gun (usually the center gun of a formation). The observer will observe the impact of the round and make a correction. The gun will apply the correction and fire again. The observer and gun will continue until the round lands within a certain distance from the target. This distance is the *adjustment threshold* and is normally 50 meters.

After the adjustment threshold is met, the observer will provide an additional correction and enter the FFE phase. The location of the last correction is used

as the center of the sheaf. The artillery unit adds the corrections from the gun that fired during the adjustment phase. The unit applies the total correction to all other guns in the unit, computes the aim points of the chosen sheaf, assigns one aim point to each gun, and then fires all guns on the target (Figure 12).

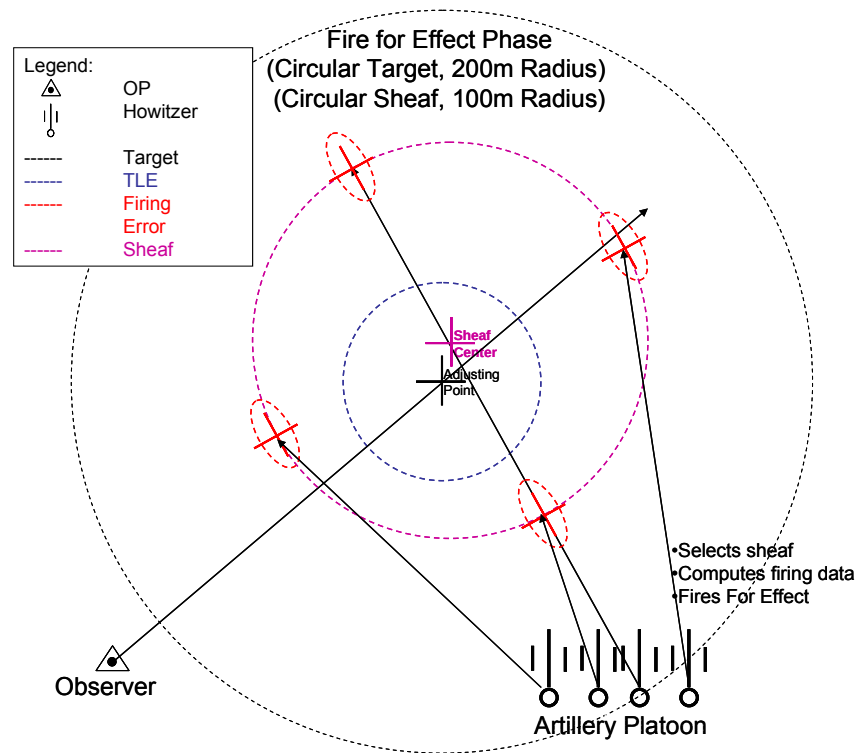


Figure 12. Representation of the FFE Phase of a Fire Mission

The number of volleys fired depends on the desired effects. This model fires 12 volleys in the FFE phase of every fire mission. This is equivalent to 48 rounds for a four-gun platoon. The minimum amount of time required to fire a 12-round volley is three minutes when all guns fire at their maximum rate of fire (4 rounds per minute for three minutes). This is considered a reasonable amount of time to allow the artillery unit to fire and then safely move before receiving enemy artillery counter-fire, given that the enemy has the acquisition assets to detect artillery fire.

b. Adjustment Technique

An observer uses one of four techniques to adjust artillery fire onto a target. This model uses the hasty bracketing technique. An observer using this technique will make bold corrections in both range and deflection, simultaneously, to ensure the

rounds will land within the adjustment threshold, 50 meters. After an impact, the distance between the adjusting point and the impact point is determined. If this miss distance is greater than the adjustment threshold, the round is adjusted in the direction of the adjusting point. The magnitude of the adjustment is equal to the miss distance plus an additional amount to ensure the round lands on the opposite side of the adjusting point. The MMM integrates an error into the observer's adjustments. The additional amount added to the miss distance has a normal distribution with mean 10 meters and standard deviation 2 meters.

c. Method of Control

The method of control indicates how the observer wants to control the time or delivery of fire. The MMM uses the "By Piece, By Round, At My Command" method. This method is a restrictive command that is used to control the time of firing of each round of each gun. Each gun fires in succession at a specified time so that only one gun fires at a time.

In this model, the guns fire at their maximum rate of fire so that one round is fired every 3.75 seconds. This method can prolong the duration of effects on the target and is best used when the intent is to suppress a target and the enemy does not have acquisition assets. The disadvantage of this method is that enemy in the target area can increase their protective posture after just one round instead of one 4-round volley.

3. The Weapon System

The artillery unit in this study is a platoon of 4 guns with 155 millimeter diameter cannon tubes. This is the basic firing unit in the Army's Unit of Action (UA). The guns have a maximum effective range of 18 kilometers (km) when firing an unassisted projectile, a maximum rate of fire of four rounds per minute for three minutes, and a sustained rate of fire of one round per minute.

a. Crew Delay Time

We consider the cannon crews to be well trained. A cannon crew has standard procedures that are followed in order to prepare both the cannon and the ammunition to fire. The time it takes a crew to conduct the procedures during a fire mission is called the *crew delay time*. The average crew delay times are obtained from the time standards in the ARTEP 6-037-30-MTP, 2000.

There are specific time standards for each type of mission. There are two crew delay times used in the study. One represents the time interval between the time the crew receives an observer's adjustment correction and the time the crew fires during the adjustment phase of a fire mission. The second delay time represents the time between firing rounds during the FFE phase.

b. Mean-Point-of-Impact (MPI) Error

The error associated with the weapon system is called the *mean-point-of-impact (MPI) error* (Figure 13). It is also called aiming error or systematic error. This error is common to all rounds fired from the same weapon and all rounds fired by a group of weapons. It is caused by variables that affect every round, such as inaccurate weapon location, inaccurate direction of fire, weather conditions, rotation of the earth, spin of the projectile in flight, average muzzle velocity variations, and human computational error.

To minimize MPI error, the artillery attempts to account for these variables and correct them. Survey techniques and global positioning systems are used to provide accurate location and direction of fire. Weather measurements are taken at designated time intervals to provide the unit with average readings at different altitudes. Muzzle velocities are recorded for each lot of projectile and propellant combination to reduce range error. Automated fire control systems are used to reduce human computational error. A precision registration fire mission can also be conducted to minimize this error.

This study assumes that a precision registration has been conducted and that each howitzer has an automated fire control system. The fire control system provides accurate self-location, accurate directional reference, accurate computations using current meteorological information (within 2 hours old), accurate muzzle velocity (MV) measurements, and automatically aims the cannon tube. Therefore, we consider four of the five Requirements of Accurate Predicted Fire met and the MPI errors resulting from the weapon to be minimal.

MPI error is bivariate normal, $MPI \sim N[(0,0),(\sigma_R,\sigma_D)]$. The two components of standard deviation are described as range error (σ_R) and deflection error (σ_D). The following is a graphical depiction of this error.

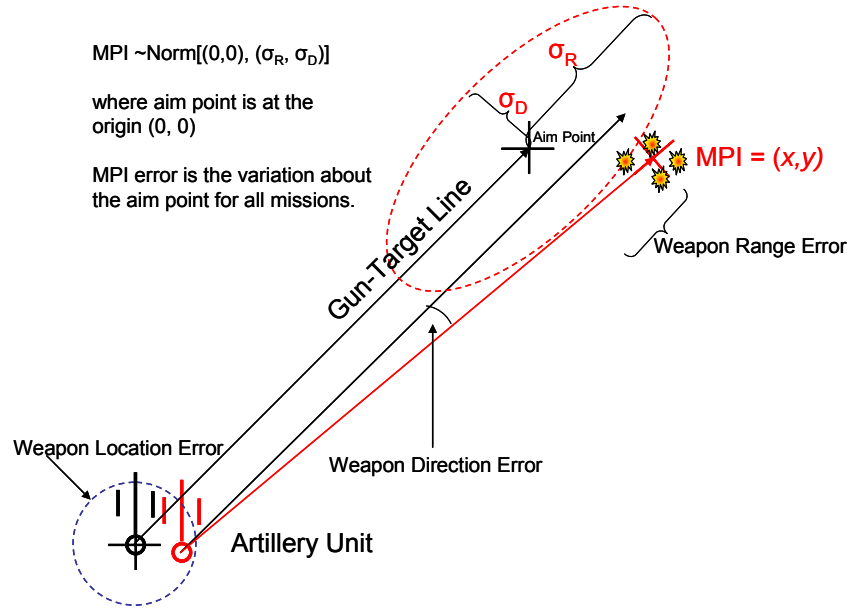


Figure 13. Representation of Mean-Point-Of-Impact (MPI) Error

It was mentioned earlier that the conventional round follows a ballistic trajectory with no guidance system and the precision-guided round can adjust its trajectory using a GPS/INS guidance system. Therefore, precision-guided munitions are not subject to MPI error. They guide themselves to the intended grid coordinate regardless of weather, muzzle velocity, etc. For conventional munitions, on the other hand, this error increases with range.

c. **Positioning**

The position of the artillery unit in relation to the target is important for determining the gun-target (GT) line. The GT line determines the orientation of the bivariate normal distribution of the firing errors. We are concerned with the GT line when firing at linear targets and when non-enemy personnel are in close proximity to the target. This is because the range error is larger than the deflection error. Therefore, when firing at a linear target, the effects will be greater when the linear target is parallel to the GT line and non-enemy personnel are safer when they are to the sides of the GT line.

The MMM assumes that the artillery unit is sufficiently far enough away from the target to consider all guns to be at the same location. The output displays the

GT line along the x-axis with the unit firing in the negative x direction (Figure 16). The adjusting point in the MMM is at the origin.

4. The Ammunition

The projectiles (rounds) used for a comparison in this study are high-explosive (HE) rounds with point-detonating (PD) fuses. The ammunition will detonate when impacting with the ground rather than an air burst. We assume that the ammunition is 100% reliable, no duds.

a. Dispersion Error

Although PGM are not subject to MPI error, both projectiles have firing errors that are independent from round to round (Figure 14). We call this type of firing error the round-to-round dispersion error (ballistic error, precision error). This error is caused by variations between rounds. Variations include differences in manufacturing of the ammunition and sudden changes in atmospheric conditions while the projectile is in flight, such as gusts of wind.

For conventional munitions, this error increases with range and has a bivariate normal distribution centered at the MPI. This error is also separated into range and deflection components. We use the preferred propellant charge designated for a given GT range to minimize this error. The preferred charge can be found in firing table G of FT 155-AM-2, 1983. The standard deviation of the range dispersion error, σ_R , causes the adjustment threshold to change to 100 meters for conventional munitions at long ranges, when it is greater than 56 meters.

For precision munitions, dispersion error depends on the type of guidance system. A GPS-guided projectile depends on the number of satellites it communicates with and can be affected by enemy electronic jamming. Its dispersion error is independent of range. The simulation model uses a 10 meter CEP dispersion error for all precision munitions at all ranges.

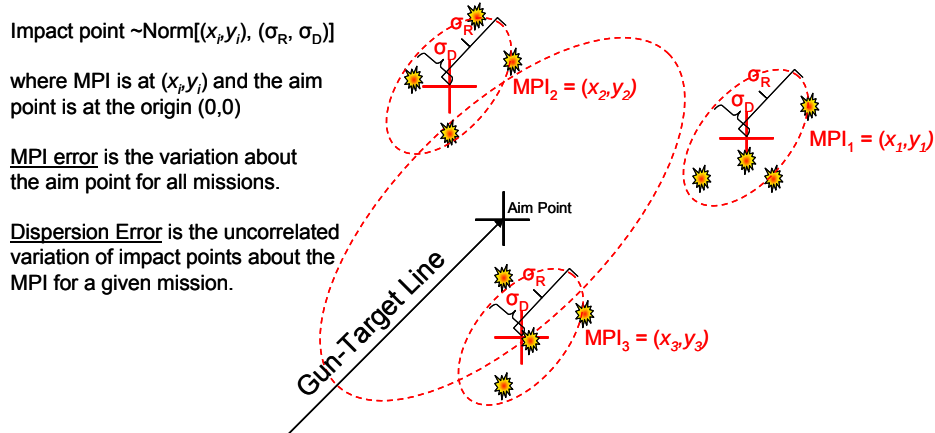


Figure 14. Representation of Dispersion Error

b. Damage Functions, $D(r)$

Each impacting round has its own independent probability of killing, wounding, or suppressing a person. The probability distribution function for each effect is represented by effectiveness curves (Figure 15). These curves depend on the type of target, the type of projectile, the type of burst (ground or air), the angle of fall of the projectile, the vulnerability (posture) of the target, and the type of terrain in the target area.

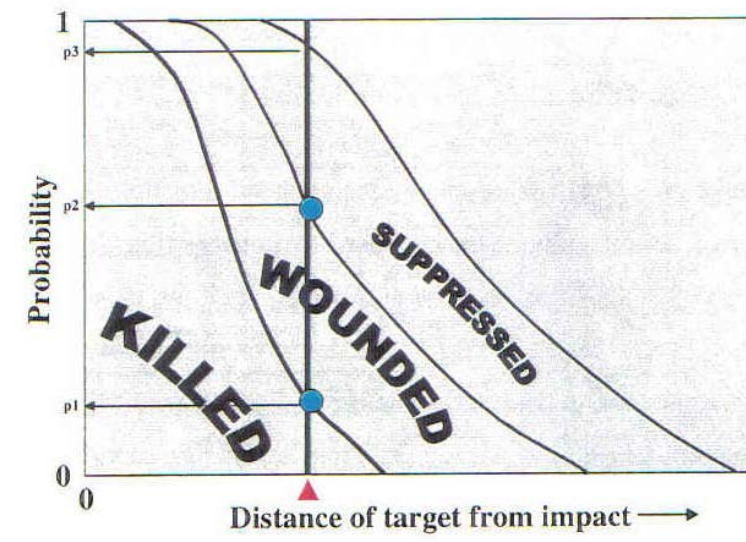


Figure 15. Representation of Effectiveness Curves (from Wald, 2003)

Damage functions, $D(r)$, are used to closely approximate the effectiveness curves. The damage function for each effect is a function of the radial distance in a plane

between the impact (detonation) point and a point target (person). This distance is called the *miss distance*, r .

The Diffuse Gaussian (Carleton) damage function is used to determine the probabilities of killing or wounding,

$$D(r) = e^{-\frac{r^2}{2b^2}} \quad (11)$$

where

$$b = \sqrt{\frac{A_L}{2\pi}}$$

A_L is the *lethal area* of the impacting round. It is defined as a measure of the damage-producing potential of a weapon when employed against a specific type of target. Mathematically, lethal area is

$$A_L = \int_{r=0}^{\infty} \int_{\theta=0}^{2\pi} D(r, \theta) r \cdot dr \cdot d\theta$$

Substituting in the Diffuse Gaussian damage function of equation (11), we have

$$\begin{aligned} A_L &= \int_{r=0}^{\infty} \int_{\theta=0}^{2\pi} e^{-\frac{r^2}{2b^2}} r \cdot dr \cdot d\theta \\ A_L &= 2\pi b^2 \end{aligned} \quad (12)$$

The lethal area for each type of ammunition is determined by experimentation and depends on the posture of the enemy and the angle of fall of the projectile at the point of impact. Actual lethal areas are classified, so this study uses approximate lethal areas derived from the classified data. We assume that both projectile types have the same lethal area in order to focus this study on the differences in effects caused by precision guidance systems.

We use the function, $D_S(r)$, developed by the U.S. Army Combat Developments Experimentation Command (CDEC) to determine the probability of suppression.

$$D_s(r) = \begin{cases} 1, & r \leq Ae^B \\ \frac{1}{B} \ln\left(\frac{r}{A}\right), & Ae^B \leq r \leq A \\ 0, & r \geq A \end{cases} \quad (13)$$

where r is the miss distance defined earlier and the parameters $A \geq 0$ and $B \leq 0$ are provided in the CDEC report (CDEC, 1976).

5. The Area Targets

The area targets in this study are stationary formations of enemy personnel on open, flat terrain. The formations closely resemble actual doctrinal infantry formations. They represent subordinate units of a motorized infantry battalion. (See FM 100-63, 1996) Each formation remains unchanged throughout the experiment. Each target is considered a high-payoff target, meaning that the commander believes the loss of the target by the enemy will contribute to the success of the friendly mission.

There are three different targets and corresponding sheafs. The first is an observation post (OP) consisting of three personnel in a 5 meter radius attacked with a converged sheaf. The second is an infantry platoon (PLT) of 32 personnel in a linear formation that is 500 meters long attacked with a linear sheaf (Figure 16). Personnel are represented by red stars, the adjusting point is represented by the black X, and aim points of the sheaf are represented by numbered boxes. The length of the target is perpendicular to the GT line.

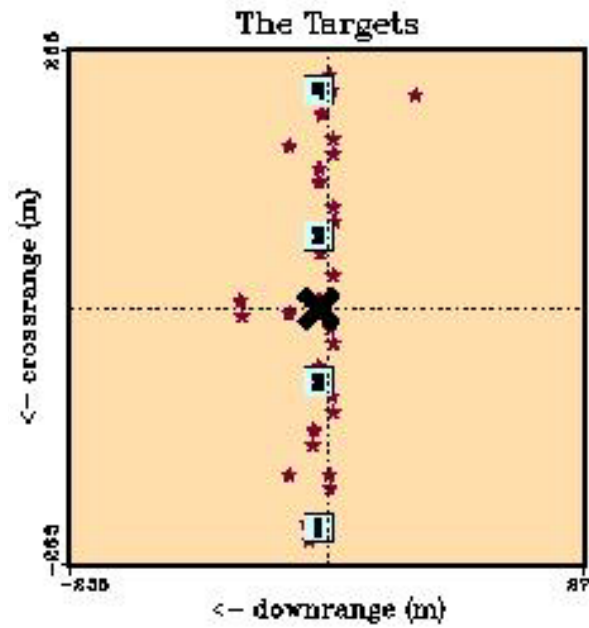


Figure 16. Mortar Mission Model (MMM) Representation of a Platoon in a Linear Formation

The third target is a company (CO) assembly area consisting of 126 personnel in an area with an approximate radius of 200 meters (Figure 17). It is attacked using a circular sheaf with a 100 meter radius.

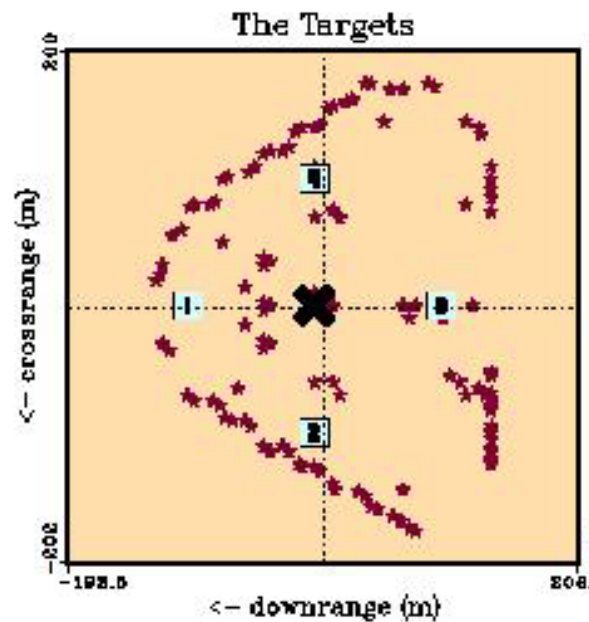


Figure 17. MMM Representation of a Company Assembly Area

a. States

A target is considered to be in one of five states and depends on the accuracy and lethality of the artillery fire. These states are *unaffected*, *suppressed*, *post-suppression*, *wounded* (neutralized), or *killed* (destroyed). We assume that a target is unaffected at the start of each engagement and then either remains unaffected or transitions into one of the other states during the course of an engagement. The transition matrix is depicted in Table 13.

	Unaffected	Suppressed	Post-Suppression	Wounded	Killed
Unaffected	P_{UU}	P_{US}	P_{UP}	P_{UW}	P_{UK}
Suppressed	P_{SU}	P_{SS}	P_{SP}	P_{SW}	P_{SK}
Post-Suppression	0	P_{PS}	P_{PP}	P_{PW}	P_{PK}
Wounded	0	0	0	P_{WW}	P_{WK}
Killed	0	0		0	1

Table 13. Transition Matrix of Artillery Effects on a Target (P_{ij} is the probability of transitioning from state i to state j at time t)

An event (impacting artillery round) must occur in order to transition into another state. The miss distance, r , from a person to the impact point is measured and then the damage functions determine the state that the person transitions into. “Killed” is the only absorbing state. A killed person stays killed. The other states are transient. A wounded person stays wounded throughout the duration of a single engagement unless killed.

The exception to the rule is the transition from the suppressed state to the post-suppression state. This is the only transition that does not require another event to occur. A suppressed person can remain in the suppressed state after another impact, can transition into the wounded or killed state after another impact, or may transition into the post-suppression state after a random period of time.

The duration of suppression is a random variable because each person is different. No study has been found that adequately determines a reasonable estimate of the mean or standard deviation of this variable. There is no clear, agreed-upon, duration

of time that a person is suppressed after each impact. The MMM assumes that it is a normal random variable with a mean of 30 seconds and standard deviation of 5 seconds. This is an assumption made by the U.S. Army Infantry Center that is based on the experience of military personnel. The model also assumes that if another impact causes a suppressed person to be suppressed again, then the duration of suppressed time begins again at the point of the last impact.

b. Posture Sequencing

A person who is affected by an impact is assumed to seek a more protective posture to decrease vulnerability to artillery fragments. This study assumes that the enemy is taken by surprise and all personnel are initially standing, the least protective posture. When enemy personnel are suppressed or wounded they move into the most protective posture they can within the time available. When suppressed enemy transition into the post-suppression state, they seek a less protective posture than while suppressed, but a more protective posture than standing. This allows them to fire on friendly forces while maintaining the lowest amount of vulnerability as possible.

The possible postures in the MMM include standing, prone, and crouching in a foxhole. The posture sequence is as follows:

Initial posture – standing

Posture while suppressed – crouching in foxhole

Post-suppression posture – prone

Post-wound posture – prone

B. INPUT DATA

1. Variables

The input variables for the model are the projectile type and the battlefield conditions discussed earlier. They include the target location error (TLE), target, and range from the guns to the target (GT Range). Each design point of the experiment represents a particular fire mission using a particular projectile under certain battlefield conditions. There are a total of 144 design points used in the model that include all combinations of the values in Table 14.

Type Mission	Projectile Type	TLE	Target	GT Range
1. Adjust Fire (AF)	1. Conventional	1. 10 m	1. OP	1. 6 km
2. No adjustment (FFE)	2. Precision	2. 75 m	2. PLT	2. 12 km
		3. 150 m	3. CO	3. 18 km
		4. 250 m		

Table 14. Input Values for the MMM

The projectile type and target are categorical variables. The projectile type is either conventional or precision. The targets are the Observation Post (point), Platoon (linear), and Company (circular) mentioned earlier.

TLE is a continuous variable. However, we only use the four target location errors (TLE) depicted in Table 15. We use a 10 meter TLE instead of zero because most observers use a GPS to determine their own location. The minimum CEP normally associated with a GPS is 10 meters.

TLE = 0 Meters (CEP)	TLE = 75 Meters (CEP)	TLE = 150 Meters (CEP)	TLE = 250 Meters (CEP)
Forward observer with laser Target area base Photointerpretation Airborne target location	Counterbattery Radar Airborne infrared system Flash ranging Countermortar radar	Sound ranging	Forward observer w/o laser Air observer Tactical air Forward observer (non FA) Long-range patrol Side-looking airborne radar Communications intel Shell reports

Table 15. Observers and Corresponding Target Location Errors (From FM 6-40, Table C-6, 1999)

GT Range is also a continuous variable. The values used in the model are between 6 kilometers (km) and 18 km. Precision-guided munitions must be fired at high angle in order to achieve enough altitude to glide onto the target. The most likely minimum range fired at high angle by the weapon system would be 6 km. The maximum range of conventional munitions with the weapon is 18 km. Therefore, it is only necessary to compare these munitions between these two values.

2. Constant Parameters

The model involves several parameters that remain constant in each experiment such as number of replications per design point (1000), the number of rounds fired in the

FFE phase of each mission (48 rounds), time parameters, error parameters, and lethal areas. The time-related parameters are depicted in Tables 16 and 17. The parameters associated with the adjustment phase of fire missions are depicted in Table 18. Some of these parameters are stochastic in nature, but are used deterministically in the models for simplicity.

	Time Delay (seconds)	Standard Deviation (seconds)
Between Rounds During Adjustment	15	0
Between Rounds During FFE	$15/4 = 3.75$	0
Observer Adjustment	10	2
Duration of Suppressed Person	30	5

Table 16. Delay Times Used in the MMM

	Time of Flight (seconds)	
Gun-Target Range (kilometers)	Conventional (Low Angle)	Precision (High Angle)
6	20.2	63.6
12	37.4	76.2
18	65.3	73.3

Table 17. Time of Projectile Flight Used in the MMM

Error	Mean (meters)	Standard Deviation (meters)
Observer Adjustment	10	2
Adjustment Threshold		
Range (km)	Conventional (meters)	Precision (meters)
6	50	50
12	50	50
18	100	50

Table 18. Adjust Fire Mission Parameters of the MMM

C. OUTPUT DATA

The Mortar Mission Model produces two graphical displays (Figures 18 & 19). One is an output display of graphs and histograms to represent the effects on the enemy and the number of rounds fired in the adjustment phase of a fire mission. The other display is a contour map representing the probability of killing or wounding a person.

We are interested in the output values of the model that represent our decision criteria (FS, FD, Risk, and Cost). The output display of graphs and histograms is used to determine FS, FD, and Cost. The “Keep-Out” distance (K) or probability of non-enemy casualties $P_C(R)$ are obtained from the contour map and used to represent Risk.

1. Determining FS, FD, and Cost from the Output Display

One thousand replications of each design point are conducted. Each replication represents a fire mission that includes an adjustment phase and FFE phase. Figure 18 represents the effects of an adjust fire mission on an enemy platoon in a linear formation. The display includes both input and output. The sub-figure in the upper left-hand corner represents the target described earlier (Figure 16). The data to the right of it include the input variables ($TLE = 10m$, $GT\ Range = 12km$). TLE is represented by $\sigma = TLE / 1.1774$. The constant input parameters are also displayed. They are the number of replications of the fire mission (1000), number of enemy personnel (32), MPI

error ($\sigma_D = 14\text{m}$, $\sigma_R = 44\text{m}$), dispersion error ($\sigma_D = 9\text{m}$, $\sigma_R = 43\text{m}$), adjustment threshold (50m), and the number of rounds fired in the FFE phase (48 rounds).

Cost is computed by dividing the total numbers of rounds used in the adjustment and FFE phases of a fire mission by the product of the CSR and the number of cannons that fired. The sub-figure in the upper right-hand corner is a histogram representing the number of rounds used in the adjustment phase. The output includes the mean (1.69) and standard deviation (1.89) of the number of rounds fired. The orange bars represent the frequency and the white bars represent cumulative frequency of rounds for 1000 replications. The average number of rounds in the adjustment (1.69) are added to the number of rounds fired during the FFE phase (48) to compute the cost of firing (Cost = 49.69/ (4xCSR)).

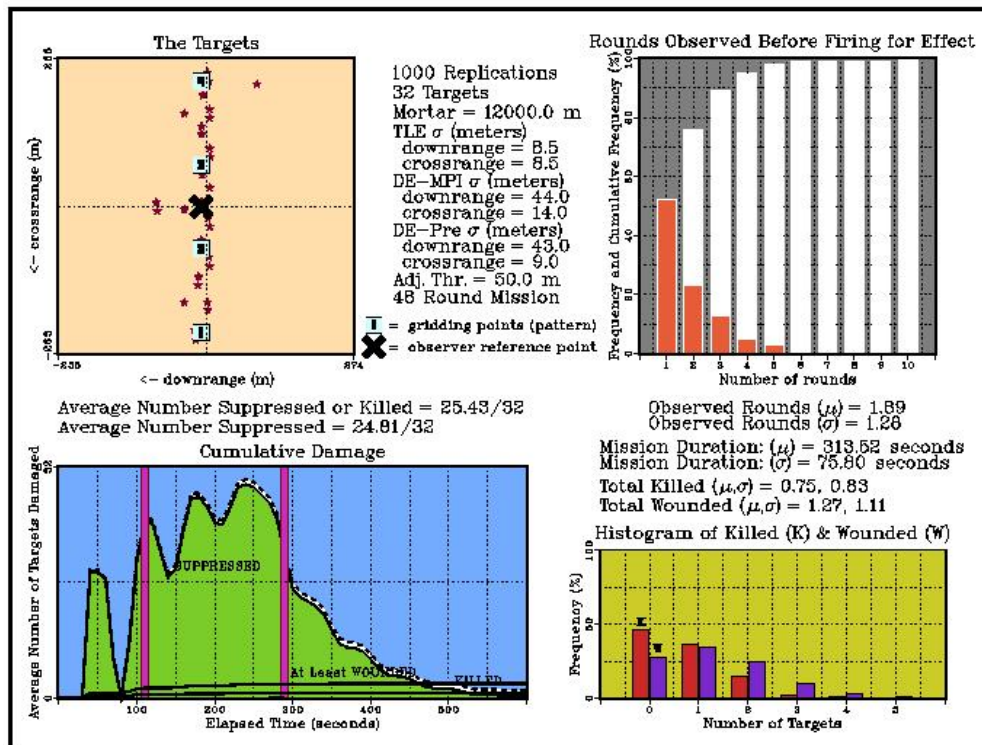


Figure 18. MMM Output Display for Effects on Enemy

FS is computed by dividing the average number of personnel suppressed or killed over a time interval by the number of personnel in the target. The graph in the lower left-hand corner represents the effects of fire over time (seconds). It includes the average number of enemy personnel wounded, killed, and suppressed throughout the adjustment

and FFE phases of the fire mission. The combined average number of killed and suppressed is represented by a dashed line with a white area beneath. The duration of suppression that is being measured is the 3 minutes (180 seconds) between the two vertical bars. The average number of suppressed and killed enemy personnel over that three minute period is 25.43. $FS = 25.43/32 = 0.79$.

FD is computed by dividing the average number of enemy personnel killed or wounded during a fire mission by the number of personnel in the target. The histogram in the lower right-hand corner represents the frequency of the number of personnel killed or wounded over 1000 replications of the fire mission. It includes the mean and standard deviation of killed (0.75, 0.83) and wounded (1.27, 1.11). $FD = (0.75 + 1.27)/32 = 0.06$.

2. Determining Risk from the Contour Map

Let $P_k(x, y)$ represent the probability of wounding or killing a person who is in the prone posture and at position (x, y) during a particular fire mission. The model determines $P_k(x, y)$ for each point in the target area using the Monte Carlo technique. The simulation produces contour maps displaying $P_k(x, y)$ for all (x, y) during a given fire mission. Figure 19 is the contour map representing the same fire mission as Figure 18.

The colors in the map correspond to the scale on the right. They represent $P_K(x, y)$ at a particular position within that color. For example, $0.15 \leq P_k(0, 0) \leq 0.20$ for a prone person at the origin $(0, 0)$ because the color at the origin corresponds to the color on the scale to the right of the map indicating 0.15 to 0.20. The bright green points along the outside of the target area represent points (x, y) where $P_K(x, y) = 0.01$ for a prone person. The outer bright yellow points represents the points where $P_K(x, y) = 0.01$ for a standing person.

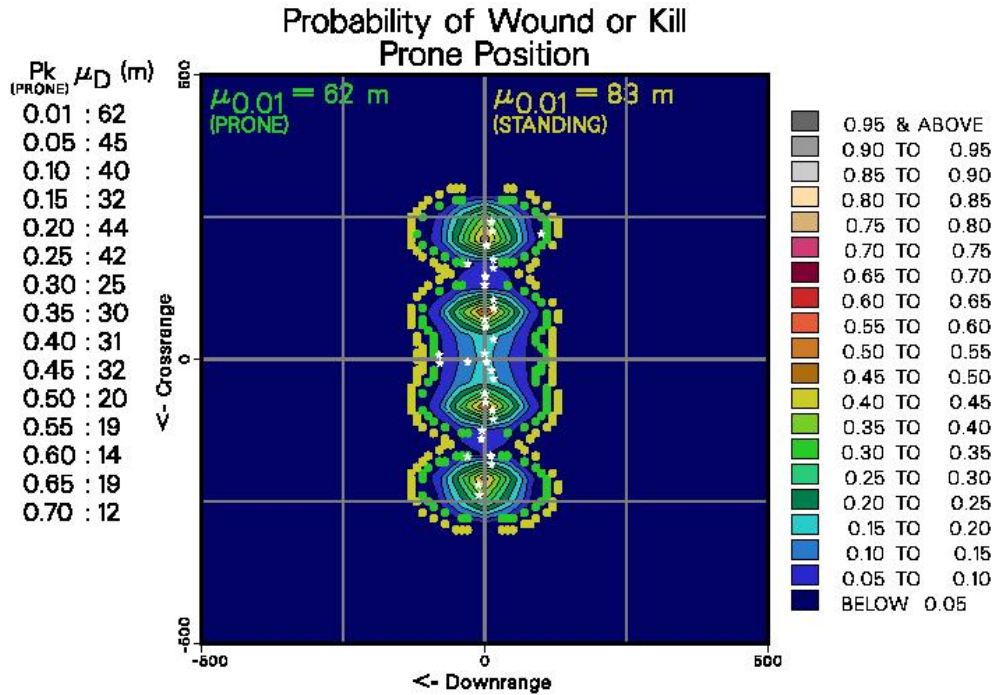
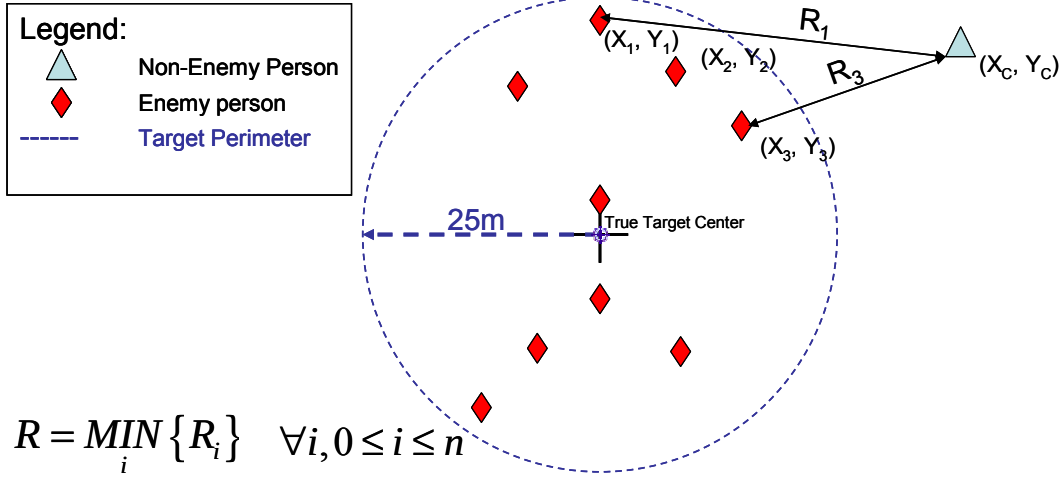


Figure 19. MMM Output Display of a Contour Map Representing the Probability of Wounding or Killing a Person in the Prone Posture During an Adjust Fire Mission with an Average of 1.69 Rounds Fired During the Adjustment Phase and 48 Rounds Fired During the FFE Phase(1000 replications)

The MMM determines the distance R , defined earlier, in the following manner. If there is an arbitrary non-enemy person that is close to the enemy formation at position (x_c, y_c) , then R is the minimum distance, R_i , between the non-enemy person and the n enemy personnel in the enemy formation at positions (x_i, y_i) for all $i = 1, 2, \dots, n$. (Figure 20).



where n is the total number of enemy personnel in the target area.

Figure 20. Determination of Risk Distance, R , of Non-Enemy Personnel in the MMM

For each probability level $P_k(x_c, y_c) = k$, for $k = 0.01, 0.05, 0.10, \dots, 1.00$, the average distance of R such that $P_C(R) = k$ is measured. This average distance is represented by μ_D in the output display on the left-hand side of the contour map. Values of $R < 0$ are not shown. The contour map also shows the average distance, μ_D , a person must be to achieve $P_C(\mu_D) = 0.01$ for both the prone and standing postures. In this case, those values are μ_D (prone) = 62m and μ_D (standing) = 83m. As mentioned before, the average distance when standing, $\mu_D = K$, where $P_C(K) = 0.01$ is the “Keep-Out Distance” ($K = 83m$).

IV. TACTICAL DECISION AID

A tactical decision aid (TDA) was developed by the author in Microsoft Excel. Microsoft Excel was chosen because it is readily available to the commander and staff of an Army UA. A restriction on software installed on computers in tactical units precludes the use of other software.

The TDA has a user interface that allows an FSO to input the variables for the target, TLE, GT Range, CSR, number of cannons firing, and the number of rounds fired in the FFE phase. An FSO is also allowed to experiment with different weights for the decision criteria.. The number of cannons firing and the number of rounds fired in the FFE phase are fixed in this study. Further study is recommended to provide data for multiple cannons firing different numbers of rounds.

A. EMPLOYMENT OPTIONS

The commander's choices in the decision problem are his employment options. Each set of battlefield conditions, CSR, and set of weights produces a different utility value for each option. The employment option with the greatest utility value is the preferred choice. If two options have the same utility value, an order of preference is used.

There are four employment options. These options are, in order of preference:

1. Conventional munitions without adjustments.
2. Precision munitions without adjustments.
3. Conventional munitions with adjustments.
4. Precision munitions with adjustments.

The TDA uses equation (10) to determine the utility of each option. The highest utility value determines the best option for the commander. The value 0 indicates that the option will produce very low effects on the enemy, very high risk to non-enemy personnel, and a very high cost of firing. The value of 1 indicates that the employment option will produce very high effects on the enemy, the risk to non-enemy personnel is very low, and the cost is very low.

B. ANALYSIS OF SIMULATION DATA

The TDA uses the output data of the simulation model to compute the utility for each projectile employment option. The data is analyzed to provide some insight into the results that are produced by the TDA.

Most of the results of the simulation were expected. We have already stated that the dispersion error and MPI error of precision munitions are independent of GT range. The output values for precision munitions reflect this. Dispersion error and MPI error are functions of range for conventional munitions, so the output values involving conventional munitions depend on range.

The results show that conventional munitions are less preferred at longer ranges. The number of adjustment rounds increases as GT range increases. FS and FD decrease as GT range increases regardless of adjustments. K increases with GT range regardless of adjustments.

The adjustment phase of a fire mission is meant to correct the TLE. Therefore, TLE is not a factor in the output values of FS, FD, and K for fire missions with adjustments, but is a significant factor for fire missions without adjustments. This is true for both projectiles, with some exceptions. K increases as TLE increases when firing precision munitions with adjustments. FD increases as TLE increases when firing conventional munitions with adjustments. The reason for these exceptions may be that some adjustment rounds cause both enemy and non-enemy casualties.

Both FS and FD decrease as TLE increases when firing both munitions without adjustments. TLE is the predominant factor for adjustment rounds. Both K and adjustment rounds increase as the TLE increases. The best values are achieved when the observer is accurate. In most cases, when the TLE is 10m, there is no benefit in adjusting fires. In fact, adjusting fire sometimes produces worse results when the TLE is 10m.

The effects of FS and FD decrease as the target gets larger for both munitions. This results because the maximum coverage area of a 4-gun platoon remains constant. The coverage area may cover small targets entirely, but cover less of large targets. This result is more evident with FD.

Target size is also a significant factor with K . As the target size increases, K decreases whether adjusting or not. Smaller targets yield larger K values. This is true of the OP because the dispersion error, alone, is greater than the radius of the target for both munitions. Therefore, many rounds will land outside of the target perimeter. The aim points of the company target are approximately 100m inside of the target perimeter. Therefore, fewer rounds would land outside of the company target perimeter. We would expect to see this trend regardless of whether adjusting fire or not.

Both FS and FD are negatively correlated with K and the number of adjusting rounds. This affirms that accurate fire produces better effects, less rounds fired in adjustment, and less risk to non-enemy personnel. The best case that all the criteria have in common is firing precision-guided munitions with an accurate observer (10m TLE) at any range. The targets influence the values differently under these common conditions. FS and FD are best when firing at an OP. K is best when firing at a company target. Adjusting rounds are unnecessary in this case for any target.

The worst cases of values depend on whether adjustments were made. The worst case for FS and FD is firing precision-guided munitions at an OP with a 250m TLE at any range when firing without adjustments. When the TLE is high, precision munitions are worse than conventional munitions because they are too accurate. In this case, the dispersion and MPI error are benefits for conventional munitions. They allow the rounds to cover a larger area. This is also the reason that firing conventional munitions at the OP with a 250m TLE without adjustments provides the worst value of K . We can see this in the following figure.

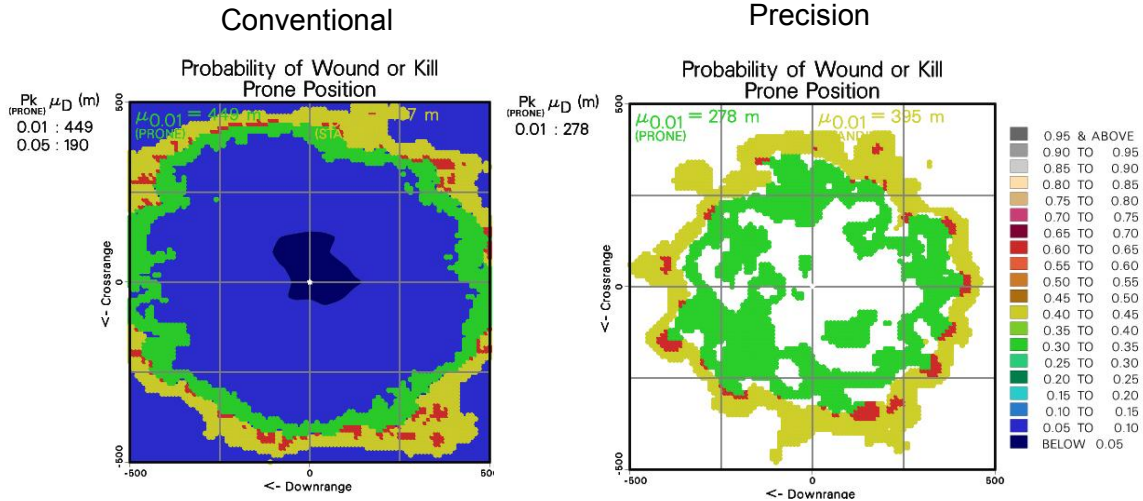


Figure 21. Comparison of Worst-Case FD and K for FFE Missions on an OP, with 250m TLE, at an 18km Range. White area means $P_k(x, y) < 0.005$ for prone.

Generally, precision munitions do not depend on the battlefield conditions when adjusting fire, although target size does affect FD and K. Therefore, as long as we adjust fire, precision munitions provide better results for all criteria. It doesn't matter what the battlefield conditions are. Precision munitions should never be fired without adjustment unless an accurate observer is used.

1. Fractional Suppression (FS)

Recall that FS is a combination of enemy killed and enemy suppressed. Small miss distances are required to provide a greater probability of kill in accordance with the damage function in equation (11). The miss distances required to suppress a target in accordance with equation (13) can be much larger. Therefore, FS is less affected by accuracy than FD. Large values of FS are observed for the same reason.

The values of FS are very high (> 0.50) with and without adjustments. This would suggest that an adjustment is unnecessary for many combinations of battlefield conditions when the desired effect is suppression. The combination of precision-guided munitions, OP, and 10m TLE provides the highest value of FS whether adjusting or not. Adjustments increased the value by only 0.3% under these conditions.

a. Fire Missions with Adjustments

Precision-guided munitions provide better FS, on average, than conventional munitions. This is a result of the combined increases in both the fraction of

enemy suppressed and the fraction of enemy killed. A two-sided paired-t 95% confidence interval (CI) for μ_D reveals that precision munitions will provide, on average, between 8.1% and 14.8% more enemy suppressed or killed on a given target.

The best value of FS is 99.7% of the target. It occurs using the precision-guided munitions with a 10m TLE (most accurate) on the Observation Post (smallest target) at any range. The worst value is 64.8% and occurs using conventional munitions with a 75m TLE on the company assembly area (largest target) at the longest range, 18 km.

FS of precision munitions has a mean $\mu_{FS} = 0.94$ and standard deviation $\sigma_{FS} = 0.05$. The values ranged from 0.84 for a company target with 75m TLE to 1.00 for an OP with 10m TLE. This difference is very small. Therefore, the battlefield conditions do not seem to significantly influence FS when using precision munitions. However, FS is lowest when the TLE is 75 m.

This phenomenon occurs because of the adjustment procedure. The peculiar thing about this TLE is that it is about the same size as the adjustment threshold, 50 m. So there will be a significant percentage of the replications in which the distance between the impact point of the first round and the adjusting point is just a little less than the threshold - so no adjustment. Therefore, the distance between the center of the sheaf used in the FFE phase and the adjusting point will be just inside the threshold ($\approx 50m$) for a significant proportion of cases.

This is not the case for the other three observers. The observer with a 10m TLE is too accurate and the observers with $TLE > 75m$ are too inaccurate. So the number of times that the final adjustment leaves the center of the sheaf just inside the adjustment threshold is much smaller. This phenomenon is clearly obfuscated by the other elements of the process, like the dispersion and MPI error of the round. This is why it is not clearly seen in the cases involving conventional munitions.

b. Fire Missions without Adjustments

There doesn't seem to be much difference between projectiles when firing without adjustment. Precision munitions provide between 0.1% and 1.4% more enemy

suppressed or killed on a given target, on average with 95% confidence. The best value of FS is 100.0% of the target. It occurs when firing precision-guided munitions on the Observation Post (OP) with a 10m TLE at any range. The worst value is 51.0% and occurs when firing precision munitions on the OP with a 250m TLE at any range.

The values for precision munitions are much worse when not adjusting and the observer is inaccurate. FS is highly dependent on the TLE for both projectiles when no adjusting rounds are used and the lack of adjustments affects precision munitions more than conventional. The significance of the TLE causes the target size and the GT range to be insignificant, although the target does have some effect on FS for both projectiles.

2. Fractional Damage

a. Fire Missions with Adjustments

A precision-guided round will provide, on average, a higher proportion of enemy killed or wounded on a target. This is similar to the FS result when adjusting fire, but the variance for precision munitions is greater for FD. We can be 95% certain that precision munitions will provide, on average, between 6.8% and 18.8% more enemy casualties on a given target.

The best value of FD when conducting adjustments is 77.7% of the target. It occurs when firing the precision-guided munitions on the Observation Post (OP) with a 10m TLE at any range. This is the same combination of conditions as the best FS with adjustment. The worst value is 3.3% and occurs when firing conventional munitions on the company target with a 150m TLE at an 18km range.

In contrast to FS, FD is highly dependent on the target for both projectiles. The effects reduce as the target gets larger. They appear to reduce exponentially as the target gets larger when firing precision-guided munitions. FD is independent of TLE and GT range when firing precision munitions.

b. Fire Missions without Adjustments

The projectiles appear to have nearly the same effects on targets, except when firing at an OP target with 10m TLE at the three ranges. In this case, precision munitions provide much higher FD. We can be 95% certain that precision munitions will

provide, on average, between 0% and 9.3% more enemy casualties on a given target. This isn't nearly as good as when firing an adjustment first.

The best value of FD when not conducting adjustments is 66.3% of the target. It occurs when firing the precision-guided munitions on the Observation Post (OP) with a 10m TLE at any range. The worst value is 0.3% and occurs when firing precision munitions on the OP target with a 250m TLE at any range. These are the same combinations as the best and worst values of FS when firing without adjustment.

3. Keep-Out Distance

The value of K is significantly lower when firing with adjustment than firing without adjustments. K has a positive correlation with adjusting rounds when firing with adjustments. The less accurate the observer is, the more adjustment rounds have to be fired and there is a greater risk of non-enemy casualties. This result supports the current procedure of adjusting fire whenever a danger close situation exists.

a. Fire Missions with Adjustments

Precision munitions provide smaller Keep-Out distances and are more preferred. We are 95% certain that precision munitions will provide, on average, a "Keep-Out" distance between 45 and 82 meters less than conventional munitions on any given target.

The best value of K when conducting adjustments is 26 meters. It occurs when firing the precision-guided munitions on the company target with a 10m TLE at any range. The worst value is 263 meters and occurs when firing conventional munitions on the OP target with a 75m TLE at an 18km range.

b. Fire Missions without Adjustments

Precision munitions provide smaller values of K whether adjusting fire or not. We can be 95% certain that precision munitions will provide, on average, between 49 and 80 meters less distance from the target perimeter than conventional munitions when not firing an adjustment. This is almost the same interval as when conducting adjustments.

The best value of K when not conducting adjustments is 26 meters. It occurs when firing the precision-guided munitions on the company target with a 10m

TLE at any range. This is the same result as when conducting adjustments. The worst value is 497 meters and occurs when firing conventional munitions on the OP target with a 250m TLE at an 18km range.

4. Number of Rounds Fired in Adjustment

The number of rounds fired in the adjustment phase of all the fire missions in this experiment is relatively low. The reason for this is the method of adjustment. Hasty bracketing is used by a relatively experienced observer who can make fairly accurate corrections. Other methods, such as successive bracketing and creeping fire, normally require more rounds.

The lowest (best) number of adjusting rounds fired when conducting adjustments is one round. It occurs when firing the precision-guided munitions on any target with a 10m TLE at any range. The highest (worst) number of adjusting rounds is 2.87 rounds and occurs when firing conventional munitions on the company target with a 250m TLE at a 12km range.

Precision munitions require fewer rounds than conventional munitions. We are 95% certain that the number of rounds used in adjustment for precision munitions will be, on average, between 0.41 and 0.59 less on a given target than conventional munitions. This does not seem like a very big difference. However, we fire at least one adjusting round for every mission in this data set no matter how accurate the observer is. The results from FS and FD show us that we don't need to fire an adjusting round when we have an accurate observer and precision munitions.

If all missions fired with a 10m TLE and precision munitions required zero adjusting rounds, then the average number of rounds required using precision munitions reduces to 0.55 to 0.95 less than conventional munitions. This is still not a very big difference, but the difference of one round could be the difference of 1-2 minutes when considering observer delay time, crew delay time, and time of flight of the projectile for every adjusting round fired. One to two minutes gives an enemy soldier plenty of time to seek a more protective posture, which means the artillery will have less effect.

The target has no effect on the number of rounds. The reason for this is that the observer is adjusting rounds onto a single adjusting point near the center of the target. It doesn't matter what the shape or size of the target is.

The number of adjustment rounds is highest when firing at 12km. The reason for this is that the standard error in range of the dispersion error at 12km is 43m and at 18km is 77m. When this error is less than or equal to 56m, the adjustment threshold is 50m. When this error is greater than 56m, the adjustment threshold becomes 100m. Therefore, the number of adjusting rounds required drops at this point (GT Range $\cong$ 14.5km) and then continues to climb again. Since 18km has an error greater than 56m, but by only 21m, we require less adjustment rounds at this range. The adjustment threshold for precision munitions remains 50m because the dispersion error doesn't change with range.

C. CASE STUDY

This is an example of how this decision aid would be used in a Unit of Action.

1. Situation

A U.S. Army infantry Unit of Action (UA) is conducting operations in a desert environment. An infantry company of the UA is attempting to rescue a small village that is being held hostage by insurgents. The insurgents are a company-size force that has established an assembly area just outside the village. They are in a good position to observe the entrance to the village and fire on anyone who attempts to enter the village. There is a ravine preventing the friendly infantry from being able to maneuver onto the enemy without first entering the village. The enemy has dug fox holes and is equipped with heavy machine guns and rocket-propelled grenades.

The field artillery battalion of the UA will be supporting the operation. The battalion has four platoons of four guns each. One platoon is available to support this mission. This platoon is approximately 12km from the center of the target.

The controlled supply rate (CSR) of conventional high-explosive rounds is 15 rounds per cannon per day. The CSR of the GPS-guided high-explosive round is 0.5 rounds per cannon per day.

2. UA Commander's Guidance for Fires

The artillery will *disrupt* the insurgent company's ability to prevent the U.S. infantry company from entering the village in order to allow the friendly company to evacuate the villagers and then destroy the insurgents.

The purpose of the mission is to save the villagers' lives. The severity of civilian casualties would be catastrophic to the mission's success.

3. Concept of the Operation

The infantry company commander believes that his company will be exposed for approximately three minutes before they are safely inside the village. The artillery platoon determines that they will need a 48 round mission fired "By Piece, By Round, At My Command". A field artillery forward observer with a GPS and laser is attached to the infantry company. The observer will be in position to observe the target and initiate the fire mission before the infantry begin to move.

4. The Solution

The UA Fire Support Officer (FSO) inputs these conditions and the CSR into the TDA. The battlefield conditions can be determined from the situation, commander's guidance, and concept of the operation. We have a company target and a 12km GT range. An observer with laser and GPS provides a 10m TLE.

The simulation output displayed in Figures 22 through 27 is examined in order to analyze the four employment options. The fire missions without adjustments will be referred to as FFE missions for simplicity. FS, FD, K, and Cost are determined from the output as discussed earlier. The criteria values for each employment option are displayed in Table 19. This table shows that there is not a dominant employment option.

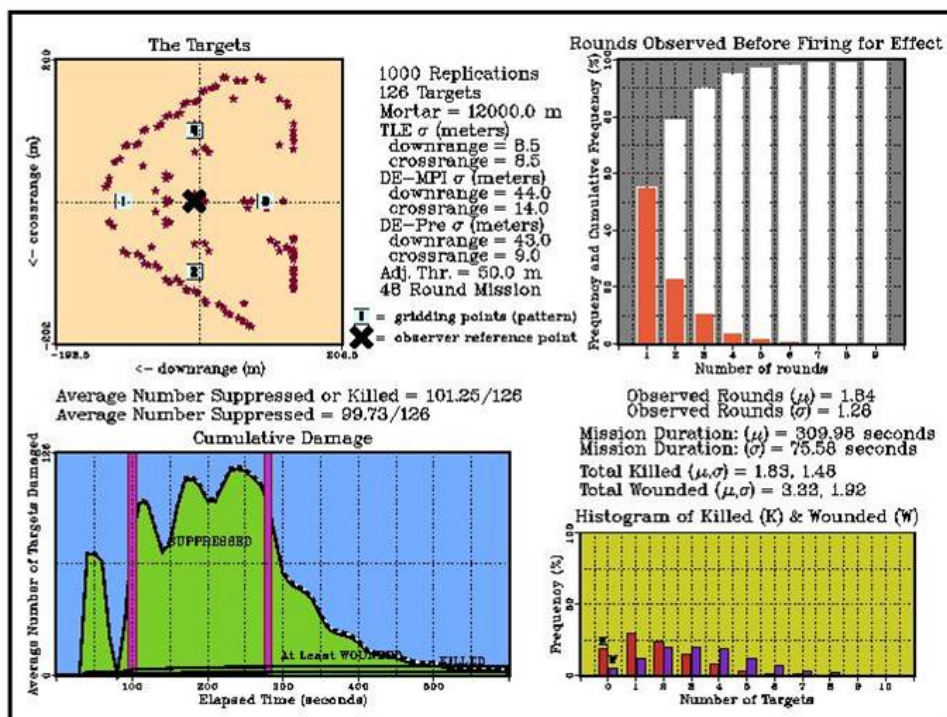


Figure 22. Graphical Simulation Output for Conventional Munitions (Adjust Fire, Company Target, 10m TLE, 12km GT Range)

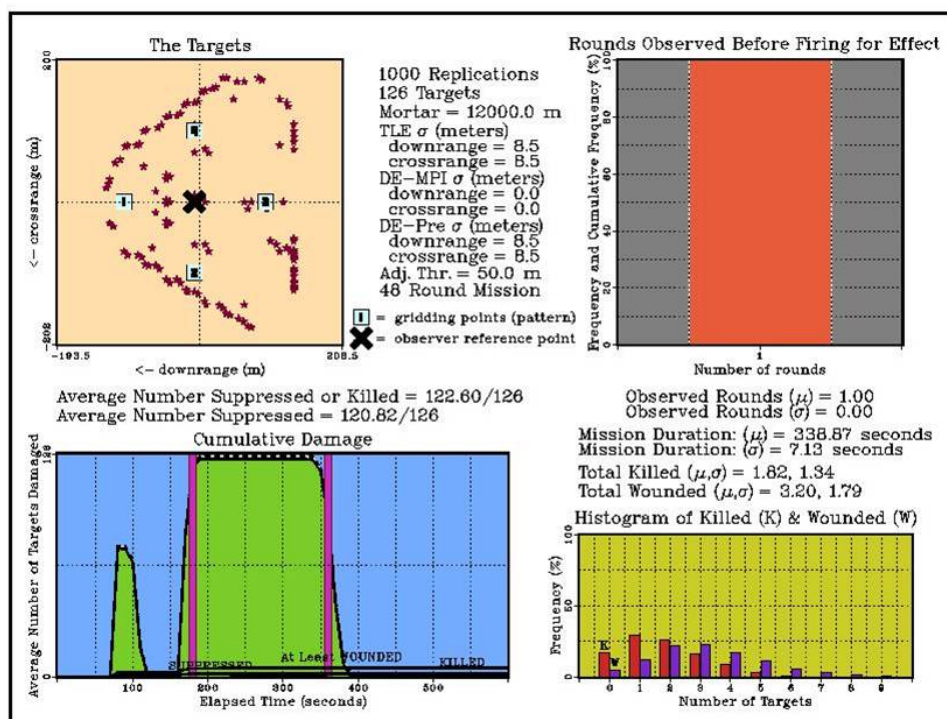


Figure 23. Graphical Simulation Output for Precision Munitions (Adjust Fire, Company Target, 10m TLE, 12km GT Range)

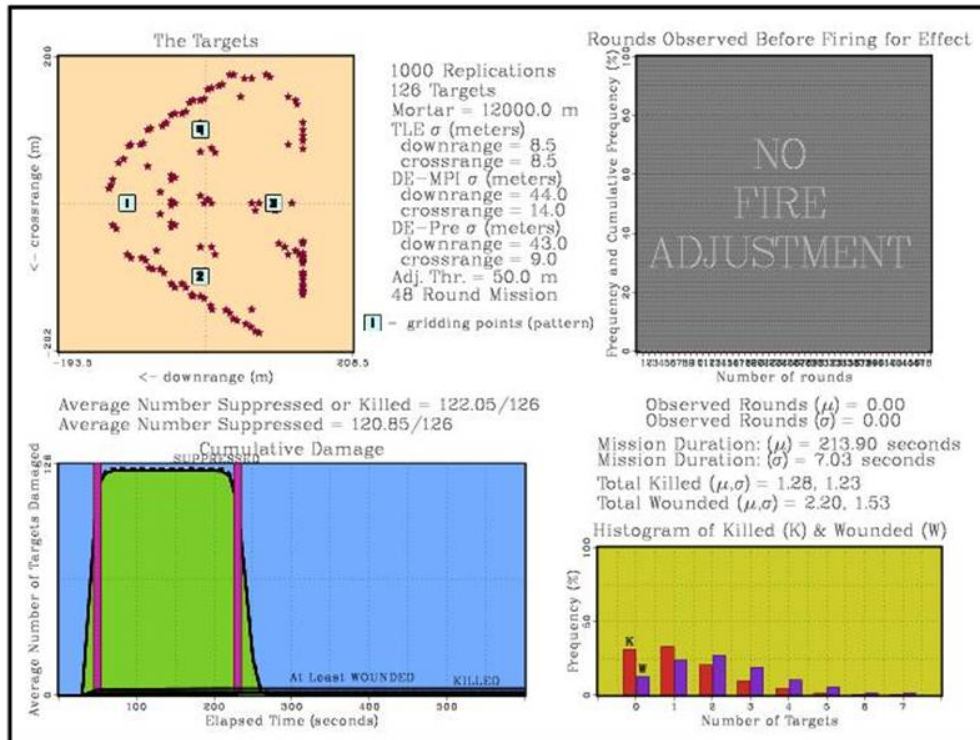


Figure 24. Graphical Simulation Output for Conventional Munitions (FFE, Company Target, 10m TLE, 12km GT Range)

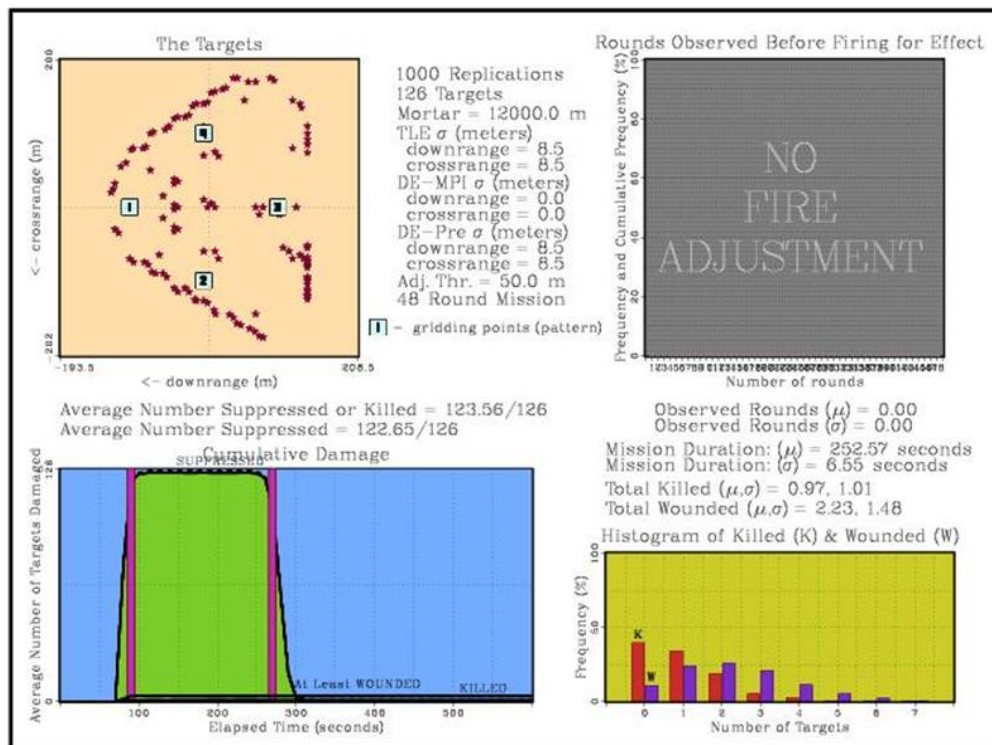


Figure 25. Graphical Simulation Output for Precision Munitions (FFE, Company Target, 10m TLE, 12km GT Range)

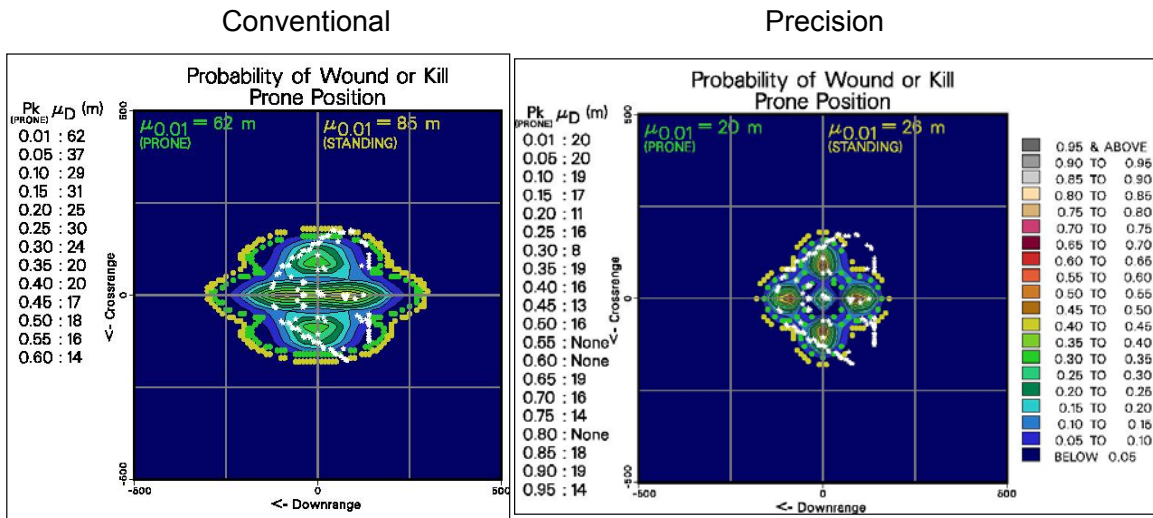


Figure 26. Comparison of Contour Maps of Both Projectiles (Adjust Fire, Company Target, 10m TLE, 12km GT Range)

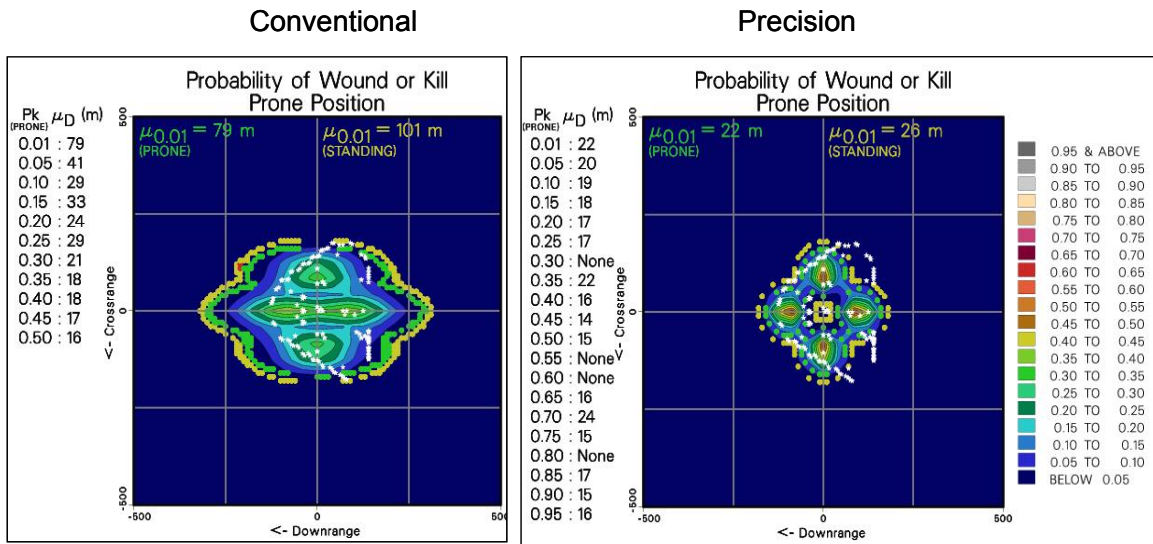


Figure 27. Comparison of Contour Maps of Both Projectiles (FFE, Company Target, 10m TLE, 12km GT Range)

Employment Option	FS %	FD %	K (meters)	Cost (days)
AF, Conventional.	80.4	4.1	84.7	0.63
AF, Precision	97.3	4.0	25.9	24.50
FFE, Conventional.	96.9	2.8	101.4	0.60
FFE, Precision	98.1	2.5	26.4	24.00

Table 19. Comparison of Decision Criteria Values for Four Employment Options Determined from Figures 22 through 27 (Company Target, 10m TLE, 12km GT Range). See Chapter III, Section C for a discussion on the determination of these values.

Figure 27 displays something unusual with precision munitions. There is a pocket in the center of the target where a person would be relatively safe. The accuracy of precision munitions confines the effects around the aim points. This causes a higher number of casualties, but within small areas. This is an undesired effect because FD decreases more substantially for precision munitions as the target gets larger.

The firing error of conventional munitions allows their effects to spread around the target. They may not be as accurate, especially at long ranges, but they can produce more casualties. In this case, conventional munitions provided 0.14 more average casualties than precision munitions when adjusting fire (Figures 22 and 23) and provided 0.34 more average casualties when not adjusting (Figures 24 and 25).

As far as suppression, there isn't a significant difference between the two mission types for precision munitions. It is not necessary to adjust fire when the observer is accurate. It is better to fire conventional munitions without adjustment when the TLE is 10m and the firing error is large. The large firing error produces higher FS when conducting a FFE mission.

The center of the sheaf of a FFE mission will be within 25.5 meters of the target center 99.7% of the time when the TLE is 10m. Adjust fire missions will cause the center of the sheaf to be further away because an adjustment correction of conventional munitions at 12km has a total range error greater than 87m.

The utility functions convert the values of Table 19 into utilities (Table 20). We wish to maximize each utility. Table 20 shows that there is not one employment option that dominates all others. This was also shown in Table 19 with the raw criteria values.

Employment Option	U(FS)	U(FD)	U(K)	U(Cost)
AF, Conventional.	0.75	0.13	0.18	0.85
AF, Precision	0.96	0.12	0.60	0.01
FFE, Conventional.	0.96	0.09	0.13	0.89
FFE, Precision	0.97	0.08	0.59	0.01

Table 20. Comparison of Utility Values for Four Employment Options (Company Target, 10m TLE, 12km GT Range). Utilities are for the values in Table 19.

Without considering weights, the option to FFE with conventional munitions provides the greatest additive value. However, this option may not provide the results that accurately reflect the commander's preferences. Therefore, the decision must consider the weights.

Determining the weights is the most difficult part. It requires the FSO to analyze the mission, enemy, terrain, firing units available, and the munitions available. The FSO uses the weight guidelines in Tables 7, 8, and 9 and the pair-wise comparison scale in Table 10 to assist with the criteria comparisons. First, the FSO uses Table 7 to determine that FS should be weighted heavier than FD based on the commander's task to disrupt the enemy. The FSO believes that FD might also be beneficial because the infantry will attack the enemy after they have completed their task of evacuating civilians. The FSO determines that FS is "moderately preferred" to FD. This is the value "3" in Table 10.

Next, the FSO determines the relationship between risk and both FS and FD. Since the commander considers the loss of any civilian to have catastrophic consequences to the success of the mission, we "very to extremely strongly prefer" risk to both FS and FD.

Finally, the FSO uses Table 9 to determine the relationship between cost and both FS and FD. The operation is offensive in a low-intensity conflict. Therefore, using Table 10, the FSO determines FD and FS to be "equally to moderately preferred" to cost. The

TDA computes the weights from these pair-wise comparisons. Figure 28 displays the solution of employment option that best meets the commander's intent.

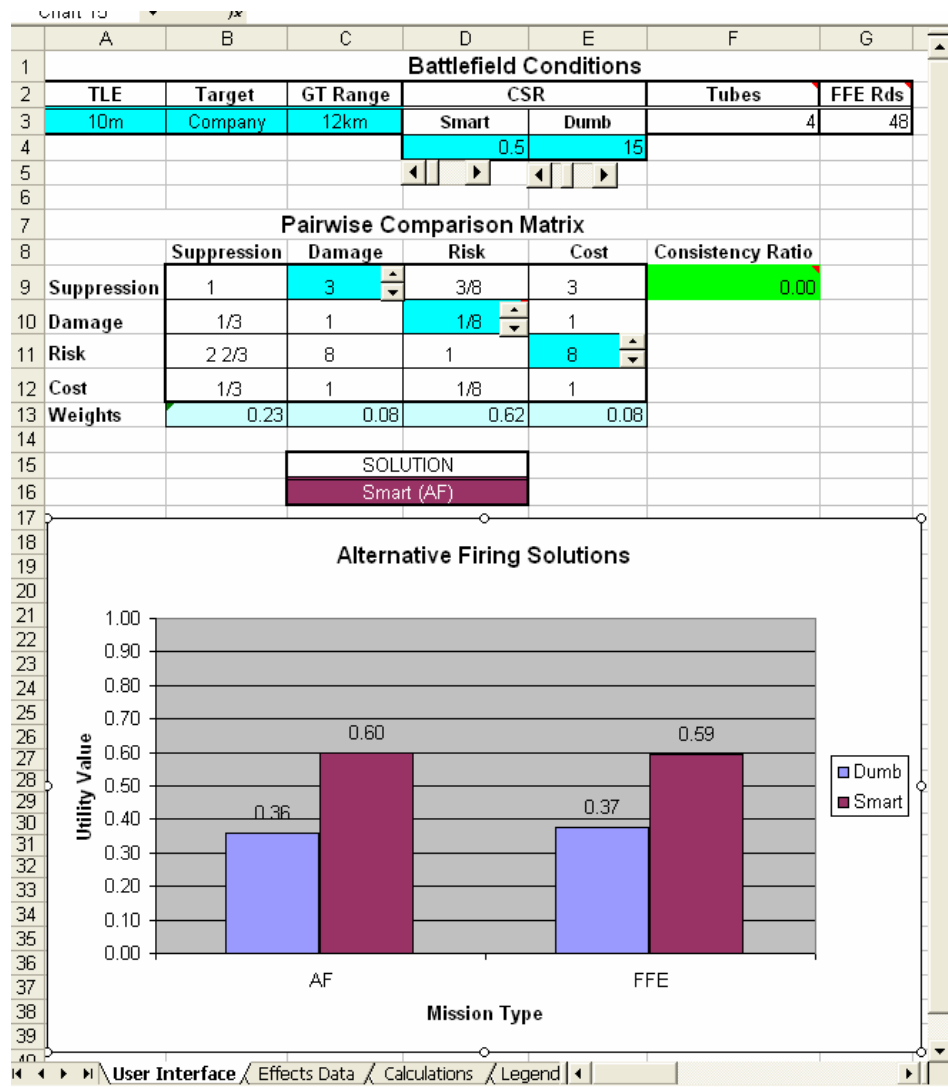


Figure 28. Excel Worksheet Displaying Decision Model. (Dumb = Conventional Munitions, Smart = Precision Munitions, AF = Adjust Fire Mission, FFE = Fire Mission without Adjustments)

The solution is insensitive to the CSR with this combination of TLE, Target, GT range, and weights. The weight for cost is only 0.08. The FSO may consider cost to be more important if the current supply of ammunition is low. In that case, the solution would be more sensitive to CSR. The comparison tables are just guidelines. The FSO must rely more on experience, understanding of the current situation, and familiarity with the commander to determine appropriate comparisons.

The results of the weights in Figure 28 are almost the same for the other battlefield conditions (Figure 29). Most of the solutions include precision munitions because risk is high for conventional munitions and it is weighted as the most important ($w_3 = 0.62$). The cost of precision munitions is very high, but it is weighted least important.

I	J	K	L	M	N	O	P
	Adjust			Harold L. La Rock, II: TLE Target Range 1 = 10m 1 = OP 1 = 6km 2 = 75m 2 = Platoon 2 = 12km 3 = 150m 3 = Company 3 = 18km 4 = 250m			
	Fire	FFE	Overall				
Conditions	Choice	Choice	Choice				
111	Smart	Smart	Smart (AF)				
112	Smart	Smart	Smart (AF)				
113	Smart	Smart	Smart (AF)				
121	Smart	Smart	Smart (FFE)				
122	Smart	Smart	Smart (FFE)				
123	Smart	Smart	Smart (FFE)				
131	Smart	Smart	Smart (AF)				
132	Smart	Smart	Smart (AF)				
133	Smart	Smart	Smart (AF)				
211	Dumb	Dumb	Dumb (AF)				
212	Dumb	Dumb	Dumb (AF)				
213	Smart	Dumb	Smart (AF)				
221	Dumb	Dumb	Dumb (AF)				
222	Smart	Dumb	Smart (AF)				
223	Smart	Dumb	Smart (AF)				
231	Dumb	Dumb	Dumb (AF)				
232	Smart	Dumb	Smart (AF)				
233	Smart	Dumb	Smart (AF)				
311	Dumb	Dumb	Dumb (AF)				
312	Dumb	Dumb	Dumb (AF)				
313	Smart	Dumb	Smart (AF)				
321	Dumb	Dumb	Dumb (AF)				
322	Smart	Dumb	Smart (AF)				
323	Smart	Dumb	Smart (AF)				
331	Dumb	Dumb	Dumb (AF)				
332	Smart	Dumb	Smart (AF)				
333	Smart	Dumb	Smart (AF)				
411	Dumb	Dumb	Dumb (AF)				
412	Dumb	Dumb	Dumb (AF)				
413	Smart	Dumb	Smart (AF)				
421	Dumb	Dumb	Dumb (AF)				
422	Smart	Dumb	Smart (AF)				
423	Smart	Dumb	Smart (AF)				
431	Dumb	Dumb	Dumb (AF)				
432	Smart	Dumb	Smart (AF)				
433	Smart	Dumb	Smart (AF)				

Figure 29. Excel Worksheet Displaying Decision Results for Various Sets of Conditions. Weights are the same as in Figure 28. (Smart = precision-guided munitions, Dumb = conventional munitions)

Precision munitions dominate the decision when we have an accurate observer (10m TLE). The solution is always to fire an adjust fire mission with conventional munitions when firing at any target with an inaccurate observer at short range (6km) and when firing at an OP with an inaccurate observer firing at medium range (12km).

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V. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

Cannon-fired, GPS-guided, precision munitions will provide the field artillery with more flexibility to conduct a wider range of fire missions. GPS-guided munitions provide quicker response than the current laser-guided munitions and require less of both the observer and the cannon crew.

Currently, cost is a major obstacle to the use of precision munitions. It makes us ask, “Why use them for anything other than precision fires on carefully selected targets?” There may come a time in the future when there will be an expectation to use cannon-fired precision munitions for every fire mission whenever non-enemy personnel are in close proximity to the target. The current question of “Why?” may change to “Why not?”

One employment option does not dominate the others. The analysis indicates that there are conditions when precision munitions would be preferred to use for area fires and suppression. Higher risk increases the preference to use precision munitions and higher cost reduces the preference.

Precision munitions do, generally, provide better results than conventional munitions. However, there are some drawbacks of highly accurate precision munitions. The lack of a large firing error (MPI error and dispersion error) is a disadvantage with an inaccurate observer. Firing without adjusting should only be done when the observer is accurate. The lack of a large firing error also limits the area of coverage of the munitions. These drawbacks are minor and can be easily overcome.

B. RECOMMENDATIONS FOR FUTURE STUDY

This study provided a comparison between the accuracies of two munitions. However, the results are only representative of two particular fire missions. The data also only approximates the true effects of the munitions because we chose not to use the actual classified data. Further study should be conducted with classified data and other factors should also be considered.

The MMM can be used to study many variations of factors that affect the outcome of fire missions. Situations should be studied that involve variations of volleys, rates of fire, methods of control, suppression times, heights of burst, munitions (i.e. DPICM, TNT, Comp B, etc.), heterogeneous targets, mixed initial postures, posture sequencing, or terrain. An experiment should determine if less precision munitions are required to produce equivalent effects as conventional munitions under certain conditions.

Once a variety of data is collected, this data should be incorporated into computer software such as the decision model developed in this study or the Advanced Field Artillery Tactical Data System (AFATDS) to assist field artilleryman with the appropriate employment option to choose. Suppression effects must be captured in order to choose the appropriate employment option when suppression is more important to the commander.

This study did not take into account the ability of the enemy to learn. If the enemy observes that a round keeps landing in the same position and is not harming him, he might be less affected by suppression. This is another drawback of the accuracy of precision munitions. The randomness of conventional munitions may be more beneficial. This is one of many human factors issues that should be studied.

C. RECOMMENDATIONS FOR CHANGES IN ARMY DOCTRINE

The U.S. Field Artillery must update its doctrine to adjust to this new era of precision munitions. There are several problems with our current doctrine that worked well for a time, but need to be updated to take advantage of current technology and current concerns.

Protecting civilians is much more of a concern now than it was in the past. Current field artillery doctrine does not provide explicit procedures to reduce the risk to civilians, only the risk of fratricide. The only reference to civilians on the battlefield is an advisement that artilleryman must follow the Geneva & Hague conventions.

Current doctrine uses the term “Danger Close” to indicate when friendly personnel are close to the target (<600 meters). This definition does not include civilian personnel and does not allow the artillery to take advantage of current technology. The definition needs to include civilians. It should also include the direction and distance that

personnel are from the target perimeter. Distance from the perimeter of a target should be used instead of intended point of impact. An observer can estimate this distance much better when reporting proximity of non-enemy personnel. It also reflects the risk better because it takes into account the size and shape of the target.

Contour maps, like those produced by the MMM, can be used to determine the risk to enemy personnel and can also be used by armor and infantry commanders to plan their assaults on enemy objectives. If the target description and location are entered into a computer along with friendly and civilian locations, then a commander can visually see the level of risk to friendly forces and civilians that a particular fire mission may produce. Alarms can be set to automatically alert that a fire mission is too risky.

An artilleryman should be able to take advantage of modern technology by inputting necessary information into a computer and receiving output as an appropriate employment option. The input should include the input already required by the AFATDS computer system as well as others, such as terrain. The employment options used in this study did not include all factors. The employment options in the AFATDS include the type of shell (i.e., HE) and fuse combination, the number of volleys to fire, and the size of the firing unit to fire. Employment options should also include rate of fire and method of control in order to maximize the desired effects of the fire. The type of guidance system (conventional, precision) will be included in the shell/fuse combination when the munitions are fielded.

The method of control used has an effect on the type of effects desired on the target. If the desired effect is suppression, then a solution that only involves the number of volleys to fire will not produce the desired effects. Given a particular target, suppression usually requires a smaller firing unit and fewer rounds than neutralization or destruction. If the number of volleys in the solution is 3, it may not suppress long enough. A cannon crew's default rate of fire is the maximum rate of fire. Many of them sometimes exceed that rate.

The method of control "When Ready" is used when destruction or neutralization are the desired effect because the cannon crews will fire at their own rate, which is usually the maximum rate of fire. An automated procedure to select the method of

control and rate of fire would maximize the effects on the enemy and provide a quicker solution than current procedures.

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ADDITIONAL READING

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